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Exploring and Safeguarding Humanity's Home in Space

Committee on a Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033

Space Studies Board

Division on Engineering and Physical Sciences

Consensus Study Report

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[2] Dr. Collado-Vega was at NASA Goddard Space Flight Center during her tenure on the decadal survey panel.
[3] Dr. Ericsson became Assistant Secretary of Defense for Science and Technology on March 29, 2024, after more than 30 years at NASA Goddard Space Flight Center.

Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **GEORGE M. HORNBERGER (NAE),** Vanderbilt University, and **DAVID N. SPERGEL (NAS),** Simons Foundation. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Preface

Decadal surveys are community-driven studies organized by the Space Studies Board of the National Academies of Sciences, Engineering, and Medicine. They are notable for their ability to sample thoroughly the research interests, aspirations, and needs of a scientific community. Requested by the National Aeronautics and Space Administration (NASA) and other federal agencies, decadal survey reports play an outsized role in defining the nation's agenda in particular areas of science for the following 10 years, and often beyond. Decadal surveys are typically led by a primary survey committee (in this report, referred to as the steering committee or the survey committee) that is responsible for the production of a consensus report. The survey committee is supported in its efforts by the work of community members organized in study panels focused on the needs of particular subdisciplines or on broader issues of concern.

This decadal survey report—the third in a series that began with the publication in 2003 of *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*[1] and continued in 2013 with the publication of *Solar and Space Physics: A Science for a Technological Society*[2]—was requested by the Heliophysics Division of NASA's Science Mission Directorate (SMD); the National Science Foundation (NSF) Division of Astronomical Sciences and the Geospace Section of the Division of Atmospheric and Geospace Sciences; the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS), and the Department of Defense (DoD) Air Force Office of Scientific Research (AFOSR).

Prior to convening the decadal survey committee, the sponsors worked together and individually with the National Academies to develop a statement of task—a contractual agreement between the National Academies and its financial sponsors—and a noncontractual guidance document that elaborated on the statement of task and included additional requests. The survey was initiated in late summer 2022. Over the next 2 years, some 80 scientists, engineers, and policy experts served on the 20-member steering committee or one of five supporting study panels. The survey committee met six times in person; it also held seven virtual multiple-day meetings and conducted more than 60 teleconferences. Each of the study panels also met two or three times in person; in addition, they met via virtual meetings and frequent teleconference calls.

[1] National Research Council (NRC), 2003, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, Washington, DC: The National Academies Press, https://doi.org/10.17226/10477.

[2] NRC, 2013, *Solar and Space Physics: A Science for a Technological Society*, Washington, DC: The National Academies Press, https://doi.org/10.17226/13060.

A primary source for community input to the decadal survey was a widely disseminated “request for information” that resulted in the submission of 450 community input papers.[3] Presentations at professional meetings also provided opportunities for dialog with the community; one or both survey committee co-chairs led discussions during summer 2022 at the following NSF-sponsored meetings: CEDAR (Coupling, Energetics, and Dynamics of Atmospheric Regions), GEM (Geospace Environment Modeling), and SHINE (Solar, Heliosphere, and Interplanetary Environment). Additional presentations during summer 2022 occurred at the 16th International Solar Wind Conference and the American Astronomical Society Solar Physics Division meeting. The survey committee co-chairs also led town halls at the fall meetings of the American Geophysical Union in 2022 and 2023.

The decadal survey also benefited from several activities that preceded its start, including a two-part webinar series held on September 30 and October 18, 2021, that was developed by the National Academies’ Space Studies Board to encourage early-career researchers to become involved with the survey; a Space Weather Workshop and interactive discussion on decadal survey plans; NASA’s Helio 2050 workshops, which provided a forum for the community to coordinate input efforts; NASA-sponsored mission concept studies; the Living with a Star Architecture Study; and products from the Space Weather Advisory Group and the National Academies’ Space Weather Roundtable, entities created following the enactment in 2020 of the “Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act” (the PROSWIFT Act).

The decadal survey’s statement of task is reprinted in Appendix A. At its highest level, it requires the decadal survey committee to

- Provide an overview of the current state of solar and space physics science and applications, including new and emerging frontiers where solar and space physics expertise enables significant advances and the space weather pipeline from basic research to applications to operations.
- Describe the highest-priority science goals to be addressed in the period of the survey.
- Develop a comprehensive ranked research strategy that provides an ambitious, but realistic, approach to address these science goals.
- Assess the state of the profession, including identification of the workforce expertise and capabilities needed to implement the scientific and technical priorities identified by the survey.

In addition to the statement of task, NASA, NOAA, and NSF provided additional counsel to the survey committee through an ancillary document (https://tinyurl.com/3zdk7cnb). This document provides greater detail on items of specific interest to the sponsors. Within the limits imposed by time and member expertise, the survey committee has endeavored to address the additional requests in this document.

In response to the statement of task and the ancillary document, this decadal survey report presents a ranked strategy of basic and applied research to advance scientific understanding of the Sun; Sun–Earth connections and the origins of space weather; the driving of the ionosphere, thermosphere, and mesosphere from the magnetosphere and the lower atmosphere; and the Sun’s interactions with other bodies in the solar system, the interplanetary medium, and the interstellar medium.

All findings, conclusions, and recommendations are the sole responsibility of the survey steering committee. As noted above, the committee was informed by the work of five study panels:

1. Panel on the Physics of the Sun and Heliosphere (SHP)
2. Panel on the Physics of Magnetospheres (MAG)
3. Panel on the Physics of Ionospheres, Thermospheres, and Mesospheres (ITM)
4. Panel on Space Weather Science and Applications (SWSA)
5. Panel on the State of the Profession (SoP)

[3] National Academies of Sciences, Engineering, and Medicine (NASEM), “Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033,” https://www.nationalacademies.org/our-work/decadal-survey-for-solar-and-space-physics-heliophysics-2024-2033.

The first three panels are discipline-oriented—similar to those developed for the previous decadal survey in solar and space physics. Two new panels were also included in response to the statement of task: the Panel on Space Weather Science and Applications (Appendix E), whose broad remit includes consideration of the science of space weather and the forecast and prediction of its impacts, and the Panel on the State of the Profession (Appendix F), which evaluated the health and vitality of the community with attention to priorities for enhancing the workforce that will be needed to implement the scientific and technical priorities identified by the decadal survey. Consideration of these topics was among the key findings in the 2020 report *Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics: A Midterm Assessment*.[4]

The three discipline-oriented science panels (SHP, MAG, ITM) were tasked to suggest science goals and elements of a research strategy for accomplishing these panel-identified goals. As seen in their reports (Appendixes B, C, and D), elements of the panel-suggested research strategies included NASA missions (larger than a medium-class Explorer), ground-based projects (NSF mid-scale and larger), theory and modeling, and programs/activities sponsored by NOAA and AFOSR.

The science panels began by reviewing the submitted community input papers; key reference documents, including reports from other National Academies studies; and agency-provided inputs such as the predecadal studies that were conducted by NASA for the Solar Terrestrial Probes and the Living With a Star programs. To address cross-panel issues, the survey also formed working groups that comprised in nearly all instances a total of six to eight internal steering committee or panel members. The working groups held one or two in-person or virtual meetings and also met regularly by teleconference. The topical areas covered by the working group were

- Access to Space
- Data Exploitation
- Theory and Modeling
- Integrating Ground- and Space-Based Observatories
- Communications Infrastructure and Innovations

This decadal survey, like the previous one, contracted with the Aerospace Corporation to perform an independent technical, risk, and cost evaluation (TRACE) of survey committee-selected NASA mission concepts that mapped to the survey's highest-priority science goals. This effort was made to increase the cost realism of notional missions and to facilitate cost comparisons among missions. Many mission concepts were included in the community input papers submitted in response to an invitation to the research community. The three discipline-oriented science panels—SHP, MAG, and ITM—mapped concepts against their prioritization of science targets in their respective disciplines and provided the survey steering committee with a short list for consideration. In addition, the SWSA panel reviewed the science panel concepts. Focusing on operational utility, the panel evaluated the potential to increase that utility through relatively small augmentations to the complement of instruments or capabilities. The survey committee ultimately determined which concepts would be sent for evaluation to the Aerospace Corporation. The process also allowed for iteration as concepts were refined; details of this process are described in Appendix G.

All decadal surveys build on an existing "program of record," both U.S. and international. The baseline program of record for the present survey includes the Geospace Dynamics Constellation (GDC) mission concept, which was highly recommended by the 2013 decadal survey. In its initial presentation to the decadal survey, NASA invited the committee to "affirm the continued priority of GDC science" and "provide input on NASA's consideration of space weather interests as part of the GDC science mission." NASA also invited the committee to "affirm the continued priority of Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC) science and to provide input on the formulation of DYNAMIC with a dependence on GDC-provided measurements."[5]

[4] NASEM, 2020, *Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics: A Midterm Assessment*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25668.

[5] N. Fox, 2022, "NASA, Kick-off Presentation: Solar and Space Physics (Heliophysics) Decadal Survey," presentation to the Committee on the Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033 on August 22, 2022, https://www.nationalacademies.org/event/08-22-2022/docs/DCB89F55C933B67062815B110279BA440147708C8DF3?noSaveAs=1.

The decadal survey's guidance from NASA regarding both missions did not change, notwithstanding the fiscal year (FY) 2024 budget request that led to a "pause" in the development of GDC,[6] or the release of the president's FY 2025 budget request,[7] which proposed the mission's cancellation, or the request from Congress in the enacted FY 2024 budget that NASA provide a plan that launches GDC by 2030.[8] In this report, the survey committee acknowledges the significant progress in the development of GDC and strongly affirms the value of GDC science and the importance of this mission in advancing the understanding and prediction of space weather. In developing its comprehensive, balanced, and ranked research strategy, the survey committee assumes a launch of GDC (and DYNAMIC) in 2030–2031.

Chapter 1, "Solar and Space Physics," the report's introduction, includes a small sampling of the science and space weather research highlights from the previous decade; it also presents the committee's strategic vision for the solar and space physics enterprise in the coming decade and beyond. The science and space weather themes that emerged from this vision are discussed in Chapter 2, "New and Emerging Frontiers in Science," and Chapter 3, "Solar and Space Physics in the Service of Humanity," respectively. The evolving solar and space physics workforce and the challenges for the next decade are discussed in Chapter 4, "Toward a Thriving Solar and Space Physics Community." Issues discussed in the previous chapters are addressed comprehensively in Chapter 5, "Comprehensive Research Strategy: A HelioSystems Laboratory and Supporting Research and Technology." The fiscal needs to realize this strategy are considered in Chapter 6, "Summary of Research Strategy and Budget Implications." Appendixes that follow Chapter 6 include each of the reports from the decadal survey panels.

This decadal survey could not have been completed without the help of numerous members of the solar and space physics community, U.S. and international; government officials; and many others who made presentations at committee meetings, hosted outreach seminars and town meetings, drafted community input papers, and participated in mission studies. Here, the survey committee would like to acknowledge the exceptionally important contributions made by the following individuals at The Aerospace Corporation: Justin Yoshida, Mark Barrera, and Leah Sobel. The committee would also like to thank officials at the sponsoring agencies for their support and engagement throughout the development of this report, especially Nicola Fox, Margaret (Peg) Luce, and Jared Leisner, NASA; Carrie Black, Zhuangren (Alan) Liu, and Lisa Winter, NSF; Elsayed Talaat and Lawrence Zanetti, NOAA; and Julie Moses, AFOSR. The committee is particularly indebted to Dr. Leisner, the survey committee's principal point of contact at NASA, who provided detailed and prompt responses to numerous information requests.[9] Last, the committee thanks David Klumpar, who served as a member of the Access to Space working group. Except for Dr. Klumpar, the working groups were composed of survey committee and panel members. While the working groups did not produce formal reports like those of the panels, their work also informed this report. The additional work of these panel and survey committee members, along with Dr. Klumpar, is greatly appreciated. The survey committee dedicates this report to the memory of Jennifer Gannon, a leader in space weather research and policy who will be sorely missed.

[6] NASA, 2023, *FY 2024 Budget Estimates*, https://www.nasa.gov/wp-content/uploads/2023/03/nasa-fy-2024-cj-v3.pdf.

[7] NASA, 2024, *FY 2025 Budget Estimates*, https://www.nasa.gov/wp-content/uploads/2024/04/fy-2025-full-budget-request-congressional-justification-update.pdf.

[8] Explanatory Statement: Division-Commerce, Justice, Science, and Related Agencies Appropriations Act, 2024, P.L. 118-42, https://docs.house.gov/billsthisweek/20240304/FY24%20CJS%20Conference%20JES%20scan%203.3.24.pdf.

[9] NASA responses to survey committee information requests may be found at https://science.nasa.gov/heliophysics/resources/2024_decadal_survey.

Summary

Over the past decade, groundbreaking explorations have unfolded throughout the heliosphere—the vast protective bubble formed by the solar wind that extends from the Sun to the outer fringes of the solar system. For the first time, humanity "touched the Sun," and two spacecraft launched in 1977 crossed the boundary of the heliosphere where the influence of the solar wind ends and the interstellar medium begins. Fundamental discoveries were made over a vast range of scales, from microscopically small plasma processes to the global interconnected solar and space physics system, advancing the understanding of physics in space and the nature of living with a star.

Today, fundamental discoveries are waiting to be made by venturing into new environments and bringing new capabilities to familiar places. The heliosphere, home to our star and our planet, remains the only known habitable system in the universe. Studying the Sun and its influence within the heliosphere is paramount. This decadal survey identifies priority science, organized by theme, to enrich understanding of the space around us and to prepare humanity for the future.

As humanity looks to the future, solar and space physicists are uniquely positioned to study the heliosphere as the only known habitable system in the universe. The theories and models that describe the interactions of a star with the atmospheres and magnetic fields of its planets are essential for understanding both how life evolved on Earth and the physical conditions that may enable life elsewhere. The next decade may witness humans setting outposts on the Moon and preparing to venture to Mars, becoming a true space-faring civilization. As the dependence on technological infrastructure both on the planet and in space grows, the impacts of space weather and the importance of understanding the Sun and its influence continues to increase. Building upon the investments of the past decade, including a fleet of small to medium-sized missions ready to launch and the recent commissioning of the world's largest solar telescope, a great opportunity has opened to realize the vision for the next decade and beyond—*to discover the secrets of the local cosmos and to expand and safeguard humanity's home in space*.[1]

This decadal survey report from the Committee on a Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033 identifies the highest-priority science for the next decade and presents a comprehensive and balanced research strategy for making measurable progress on this science. As discussed in the preface, the statement of task is broader than those of the previous two decadal surveys in solar and space physics (NRC 2003, 2013).

[1] Earth's neighborhood in space—the local cosmos—provides a uniquely accessible laboratory in which to study the behavior of space plasmas (ionized gases) in a wide range of environments. By taking advantage of our ability to closely scrutinize and directly sample the plasma environments of the Sun, Earth, the planets, and other solar system bodies, we can test our understanding of plasmas and extend this knowledge to the stars and galaxies that we can view only from afar (NRC 2004).

Guided by this statement of task and additional counsel contained in the study approach, recommendations made to the study sponsors, the Air Force Office of Scientific Research (AFOSR), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the National Science Foundation (NSF), constitute an ambitious but realistic approach for realizing scientific and space weather advances and a vision for solar and space physics.

S.1 A VISION FOR SOLAR AND SPACE PHYSICS

Observing the space environment close to home enables detailed study of processes at work throughout the universe, and a close-up view of the system-level interactions between a star and its planets. Ultra-high-resolution images, out of reach for any star other than the Sun, have revealed turbulent structures, each the size of Texas, bubbling on the surface of the Sun. These constant motions transport energy from the solar interior to its surface, from which it can travel through space toward the planets. Understanding the changing Sun is critical for understanding its impacts on Earth. While Earth's upper atmosphere is influenced by the Sun and the space environment, it is also driven from below by internal atmospheric processes. Studies of Earth's upper atmosphere reveal the interplay between externally and internally driven atmospheric processes. Earth's upper atmosphere is in fact far from quiet. Plasma bubbles in the ionosphere—stark voids in the charged plasma enveloping Earth—impact everyday lives by disrupting global positioning system signals that travel through the ionosphere.

Exploration is driven by humanity's fundamental curiosity about the world, and solar and space scientists have always been intrepid explorers. In addition, with society increasingly reliant on technological systems and on the verge of a new era in space exploration, research knowledge has become essential to advance the applied science of space weather. The increasing importance of space weather was recognized by lawmakers with the enactment of the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT) in 2020 (P.L. 116-181). Its importance to the U.S. economy is also illustrated by comments from Ajit Pai, former Chairman of the Federal Communications Commission, who stated, "Whether they know it or not, all companies will be space companies" (National Space Society 2019).

Thus emerges a two-part vision and mission for solar and space physics for the coming decade: research and exploration to discover the secrets of the local habitable cosmos, and applied science to expand and safeguard humanity's home in space (Figure S-1). The first part of the mission reflects the curiosity-driven motivations for advancing solar and space physics research. The second part reflects the increasing importance of space weather for society. While these are two distinct and equally important reasons for investing in solar and space physics, they are integrally linked and have overlapping scientific goals; progress on one part of the mission invariably enables progress on the other.

S.2 A VISION FOR A HEALTHY AND VIBRANT COMMUNITY

The vision is only realized with a vibrant and engaged solar and space physics community. Workforce needs and challenges evolve, and continual assessment and improvements to the state of the profession are warranted. The study committee's vision for the profession is a unified solar and space physics community with a diverse workforce that engages in interdisciplinary collaborations and makes advances in scientific research and practical applications.

The identity for the field needs to be solidified. "Solar and space physics" is one umbrella term that encompasses the different components of a discipline that includes solar, heliospheric, magnetospheric, ionospheric, thermospheric, mesospheric, and space weather communities and is the name adopted here for lack of a generally accepted alternative. The lack of a common identity was raised in the 2013 decadal survey report *Solar and Space Physics: A Science for a Technological Society* (NRC 2013; hereafter the "2013 decadal survey") and continues to hinder the community's ability to articulate broadly its science and applications, as well as to assess the state of the profession. A common and recognized name and identity for the field would benefit efforts in data gathering, recruitment, education, and public outreach.

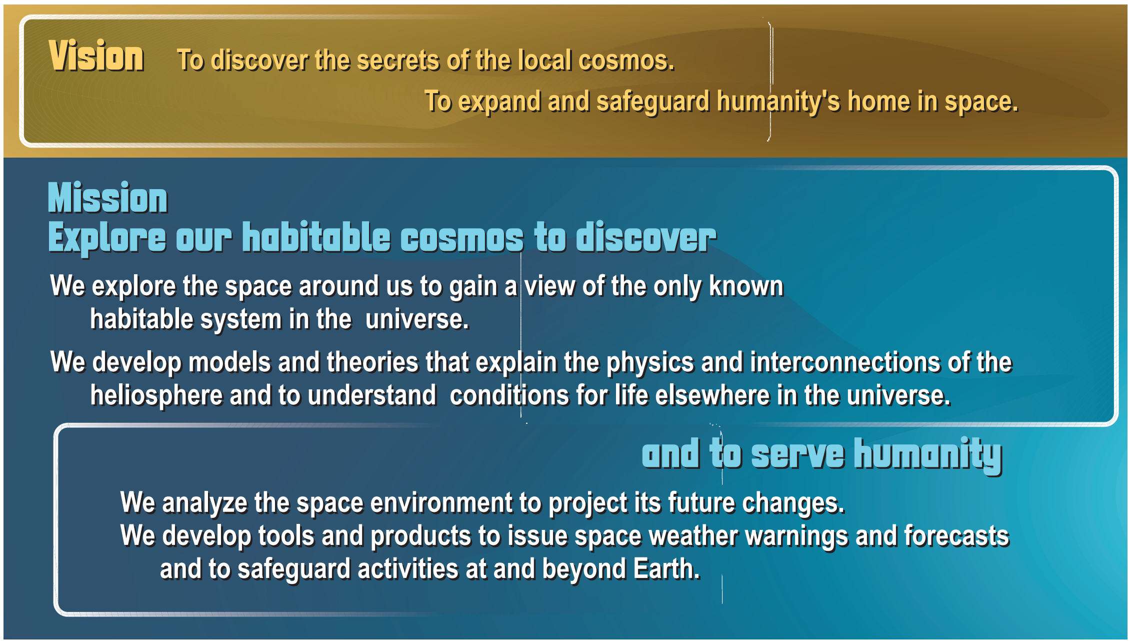

FIGURE S-1 Solar and space physics vision and mission for the next decade and beyond.
SOURCE: Created by AJ Galaviz III, Southwest Research Institute.

S.3 FRONTIERS IN SOLAR AND SPACE PHYSICS RESEARCH

The vision and mission for solar and space physics translate into a broad set of themes that serve as a roadmap for the science and space weather goals of the decade (Figure S-2) and for the future workforce needed to achieve them.

- Science themes
  - Sun–Earth–Space: Our Interconnected Home
  - A Laboratory in Space: Building Blocks of Understanding
  - New Environments: Exploring Our Cosmic Neighborhood and Beyond
- Space weather themes
  - System of Systems: Drivers of Space Weather
  - Space Weather Responses of the Physical System
  - Space Weather Impacts on Infrastructure and Human Health

The three science themes recognize the interconnections between the parts of the heliosphere; reaffirm the importance of understanding the fundamental processes from which this dynamic, interconnected system is constructed; and embrace the expansion of the field to new environments. Achieving a level of understanding that enables prediction requires a systems science approach and an understanding of the space weather drivers and impacts on physical and technological systems as well as on humans in space, in the air, and on ground. The three space weather themes encompass these three aspects of space weather research.

For each science theme, guiding questions steer the research of the coming decade (Figure S-3). Within each guiding question, research focus areas were identified for which measurable progress can be made. Most questions and focus areas are not specific to regions of space or to subdisciplines of the field; rather they were formulated to capture the community's common goals and interests. Questions and focus areas emerged from the synthesis of science questions developed by the three discipline-oriented science panels of the study (the Panels on the Physics

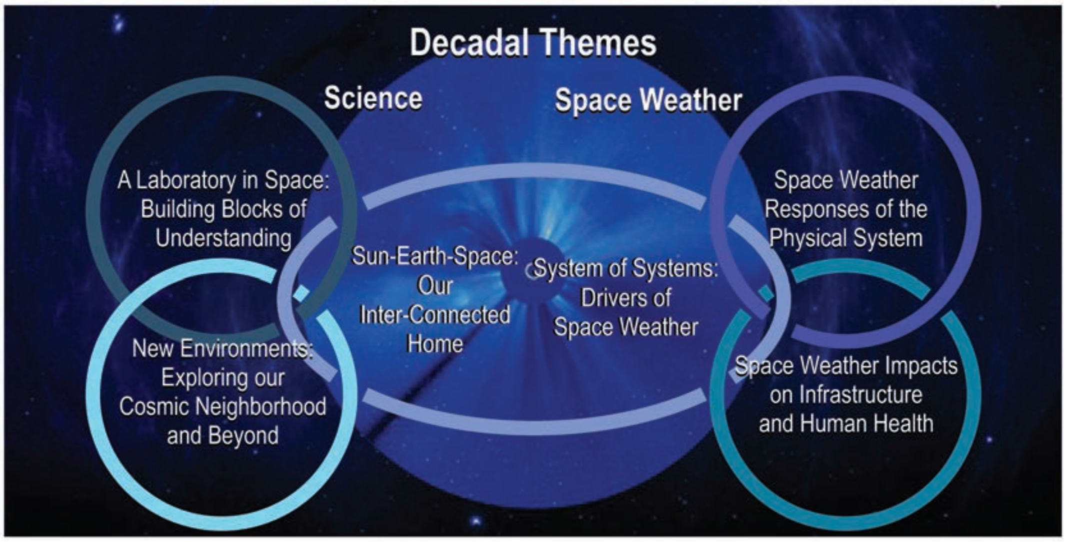

FIGURE S-2 Schematic illustrating the interlinked science and space weather themes, effectively forming "two sides of the same coin." These themes capture opportunities for discovery and progress as part of the dual mission of solar and space physics.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Center image from NASA, U.S. Naval Research Laboratory.

of the Sun and Heliosphere [SHP]; the Physics of Ionospheres, Thermospheres, and Mesospheres [ITM]; and the Physics of Magnetospheres [MAG]). The work of the panels was informed by 450 white papers (hereafter referred to as "community input papers").

Space weather research is driven largely by the needs of space weather users such as the communications, aviation, electric power, and satellite industries, as well as the U.S. government. The steering committee chose a different structure for space weather research goals to reflect this difference. The Panel on Space Weather Science and Applications identified a comprehensive set of target outcomes that were prioritized by the steering committee. The steering committee then identified research focus areas under the umbrella of three broad themes (Figure S-4) where progress is needed to achieve the prioritized outcomes. The relationship between the themes, research focus areas, and prioritized operational outcomes achievable within the next decade is shown in Table S-1. System science is central to space weather research. This is reflected in the "System of Systems" theme—a term which recognizes that the Sun–Earth system itself comprises many other systems, all of which interact. These interconnected systems have distinct physical responses to space weather drivers and associated impacts on human infrastructure and health; the two remaining themes reflect these aspects of space weather.

Together, this collection of themes—with their guiding questions and research focus areas—captures the current state of the field and its most pressing questions. The themes are broad, signifying the possibilities for scientific growth in the future, while the focus areas are targeted, identifying where measurable progress is possible in the next decade.

Further unifying scientific research and space weather application is the realization that advancement of both requires a vibrant and engaged solar and space physics community. Focus areas of improvement for the state of the profession are organized into the following four themes: Demographics of the Workforce, Solar and Space Physics Education, DEIA+,[2] and Expanding Public Outreach and Participation.

With research focus areas identified for science, space weather, and the state of the profession, a comprehensive research strategy was developed, reflecting the intimately linked nature of these goals.

[2] DEIA+ represents a wide range of topics encompassing diversity, equity, inclusion, accessibility, anti-racism, accountability, and more.

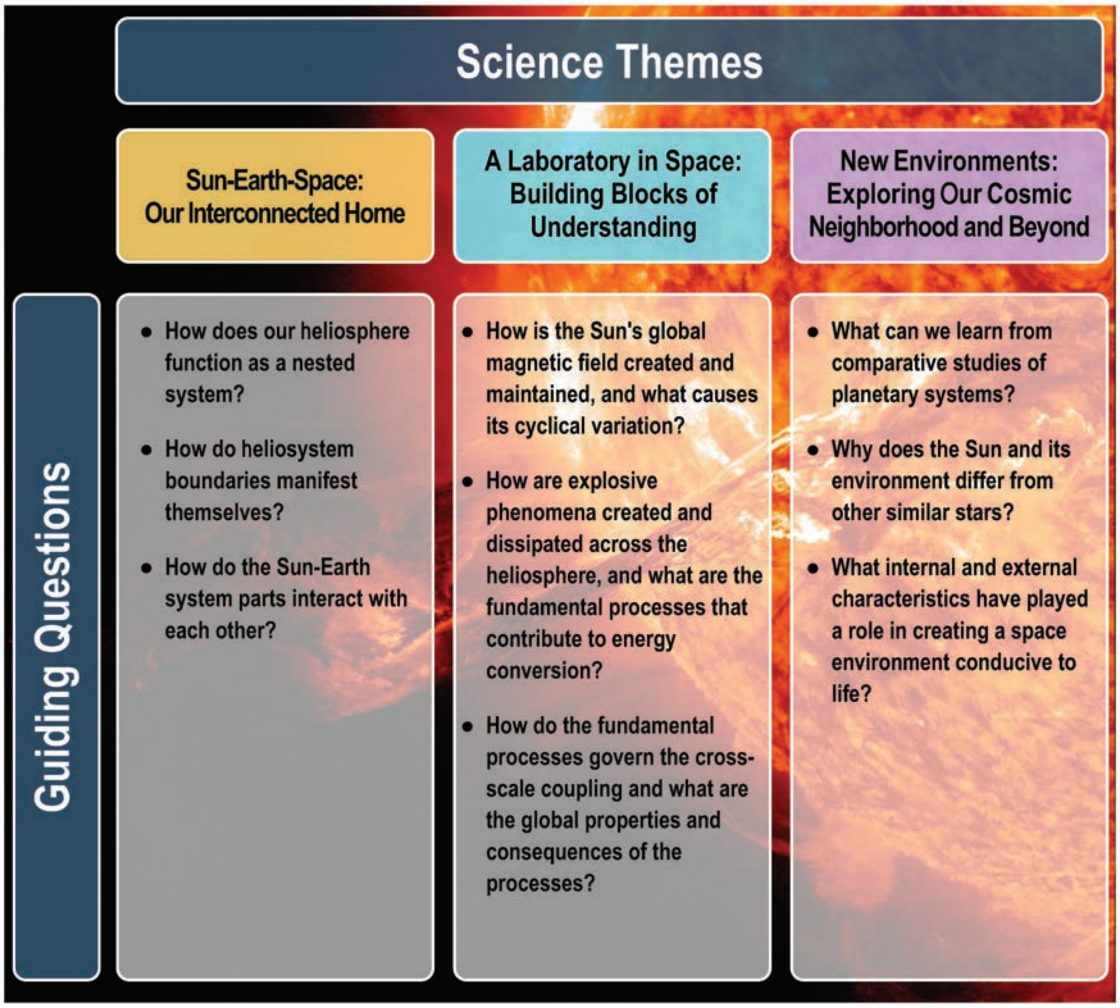

FIGURE S-3 Three science themes and their associated guiding questions. Research focus areas (not shown here) are contained within each question. Implementing the research strategy in the next decade results in significant progress on most of these focus areas and, consequently, progress on the guiding questions.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Background image from NASA/Goddard Space Flight Center.

S.4 THE COMPREHENSIVE RESEARCH STRATEGY

This decadal survey recommends a comprehensive and balanced research strategy that advances the solar and space physics two-pronged mission (Figure S-1)—the framework needed to make progress on all areas within each science and space weather theme. The strategy includes three elements (Figure S-5): an integrated HelioSystems Laboratory (HSL) to coordinate the collection of data; the DRIVE+ initiative to organize the supporting research and technology programs that enable the scientific community to produce scientific results; and preparations for the decade and beyond to prioritize investments in preparation for future endeavors. The strategy includes recommendations in each of these areas, summarized in Section S.5 below.

The strategy is *comprehensive* because it addresses all the research focus areas within each science and space weather theme, and it includes contributions from NASA, NOAA, NSF, and AFOSR, as well as international partners. The strategy is realized only through combined investments by these agencies and partners in ground-based

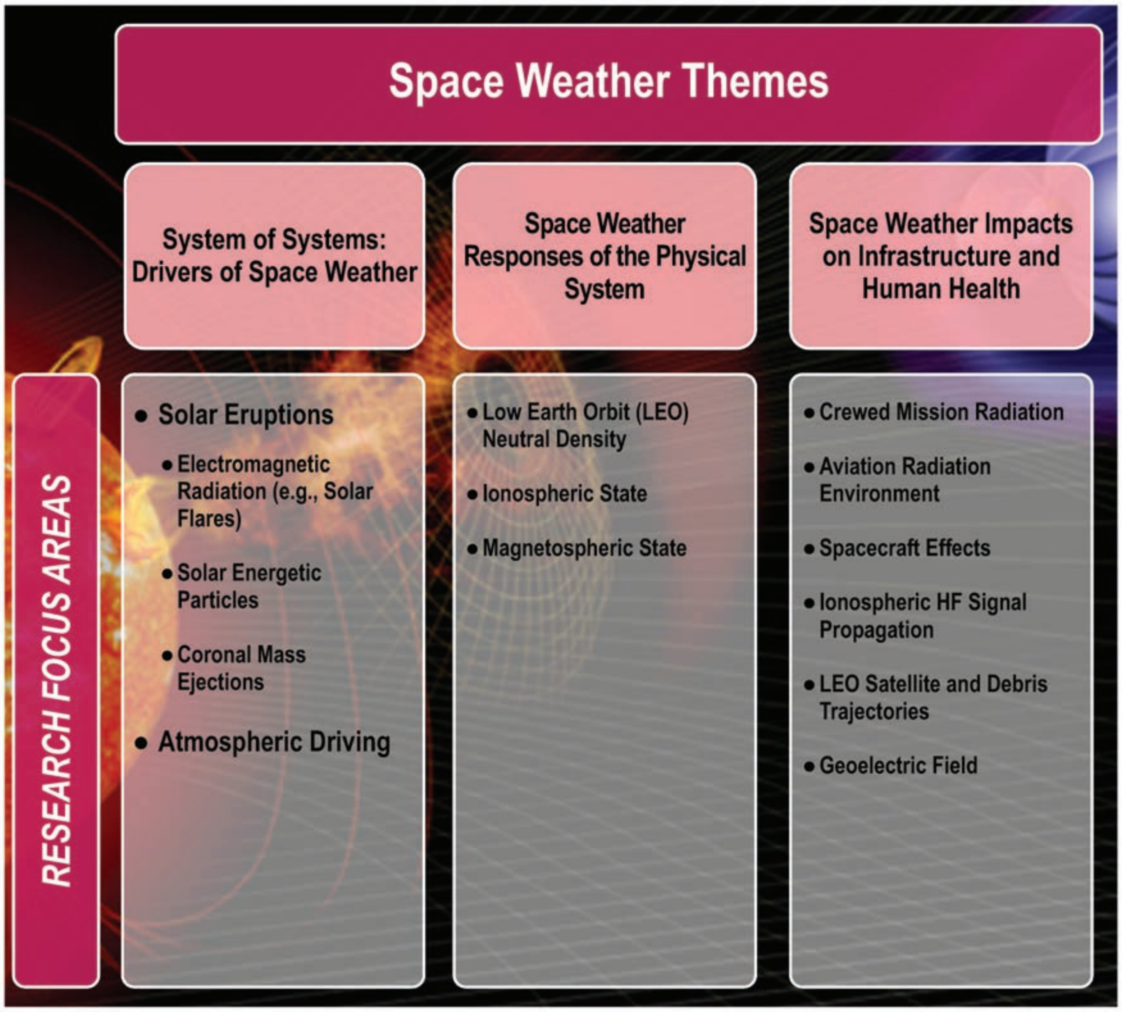

FIGURE S-4 Three space weather themes and their associated research focus areas. Each research focus area has operational outcomes (shown in Table S-1). Implementing the research strategy in the next decade results in significant progress on most focus areas and, consequently, progress on the operational outcomes.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Background image from NASA.

and space-based observations, theory and modeling, and the evolving and expanding workforce necessary to meet the broader needs of the field. Moreover, the strategy addresses a new level of cooperation between these agencies and partners that is needed to achieve systems-level science and space weather progress in the next decade.

The strategy also addresses the lack of a common identity for the solar and space physics community. There are challenges to deciding on a common name that are rooted in the different orientations of U.S. agencies engaged in solar and space physics research and operations, and even different divisions within an agency. This decadal survey recommends that agencies work together to support an entity, such as a solar and space physics consortium, that could address this issue. Such a consortium that solicits input from the community could be an effective mechanism for identifying a common name for the field and promoting efforts in data gathering, recruitment, education, and public outreach.

The strategy is *balanced* because significant progress on the aspirational decadal themes (Figure S-2) requires contributions from the entire solar and space physics community and from the widest possible range of missions and

TABLE S-1 Space Weather Operational Outcomes That Are Achievable in the Next Decade

Space Weather Themes	Research Focus Areas	Operational Outcomes That Are Achievable in the Next Decade
System of Systems: Drivers of Space Weather	Solar flares and solar energetic particles (SEPs)	>12-hour forecast for solar flares and >6 hours for SEPs
	Coronal mass ejections	12-hour forecast for coronal mass ejections and their magnetic fields
	Atmospheric driving	Quantify the contributions of gravity waves that may seed ionospheric irregularities that produce scintillations
Space Weather Responses of the Physical System	Low Earth orbit (LEO) neutral density	24-hour forecast of thermospheric density during geomagnetic storms for LEO spacecraft operators
	Ionospheric and magnetospheric states	Nowcast of ionospheric and magnetospheric state parameters including radiation environment, auroras, and ionospheric currents
	Reanalysis	Reanalysis capability for forecast/nowcast models to assess and validate models and forecast methods
Space Weather Impacts on Infrastructure and Human Health	Crewed mission radiation	Characterize and monitor space radiation environment for crewed and robotic missions
	Aviation radiation environment	Aviation radiation nowcasts and forecasts during large SEP events
	Spacecraft effects	Forecasts of spacecraft effects with multiday lead time
	Ionospheric high-frequency (HF) signal propagation	1-hour ionospheric HF signal propagation disturbance forecasts
	LEO satellite and debris trajectories	Significantly improved models for LEO satellite and debris trajectories
	Geoelectric field	1-hour geoelectric field variation forecasts with 200 km spatial resolution for power system operators

NOTES: Because space weather is outcome-driven, each theme has identified focus areas with specific operational outcomes. Implementing the integrated research in the next decade results in the operational outcomes for the focus areas.

projects. The strategy provides opportunities for discovery and understanding in solar and heliospheric, magnetospheric, and ionospheric–thermospheric–mesospheric physics as well as for meeting the space weather imperatives of the nation. The recommended actions are also balanced in mission complexity and project costs. In the next decade, the strategy provides ample opportunities for the community to participate in frequent small missions and projects as well as targeted opportunities for flagship missions and large facilities. Less frequent flagship missions and projects, with their expanded resources, make significant progress on a wide range of the science and space weather themes while more frequent, smaller missions and projects make significant progress on many targeted areas within these themes. Last, scientific progress requires a balance between large projects and support for research, technology, and workforce, as well both near-term and long-term planning. The three components of the research strategy, the HSL, DRIVE+, and preparation for beyond the decade, work together to achieve this balance.

In addition to being comprehensive and balanced, the research strategy for the next decade is ambitious but also realistically achievable. It addresses ambitious and important science and space weather goals and is *realistic*

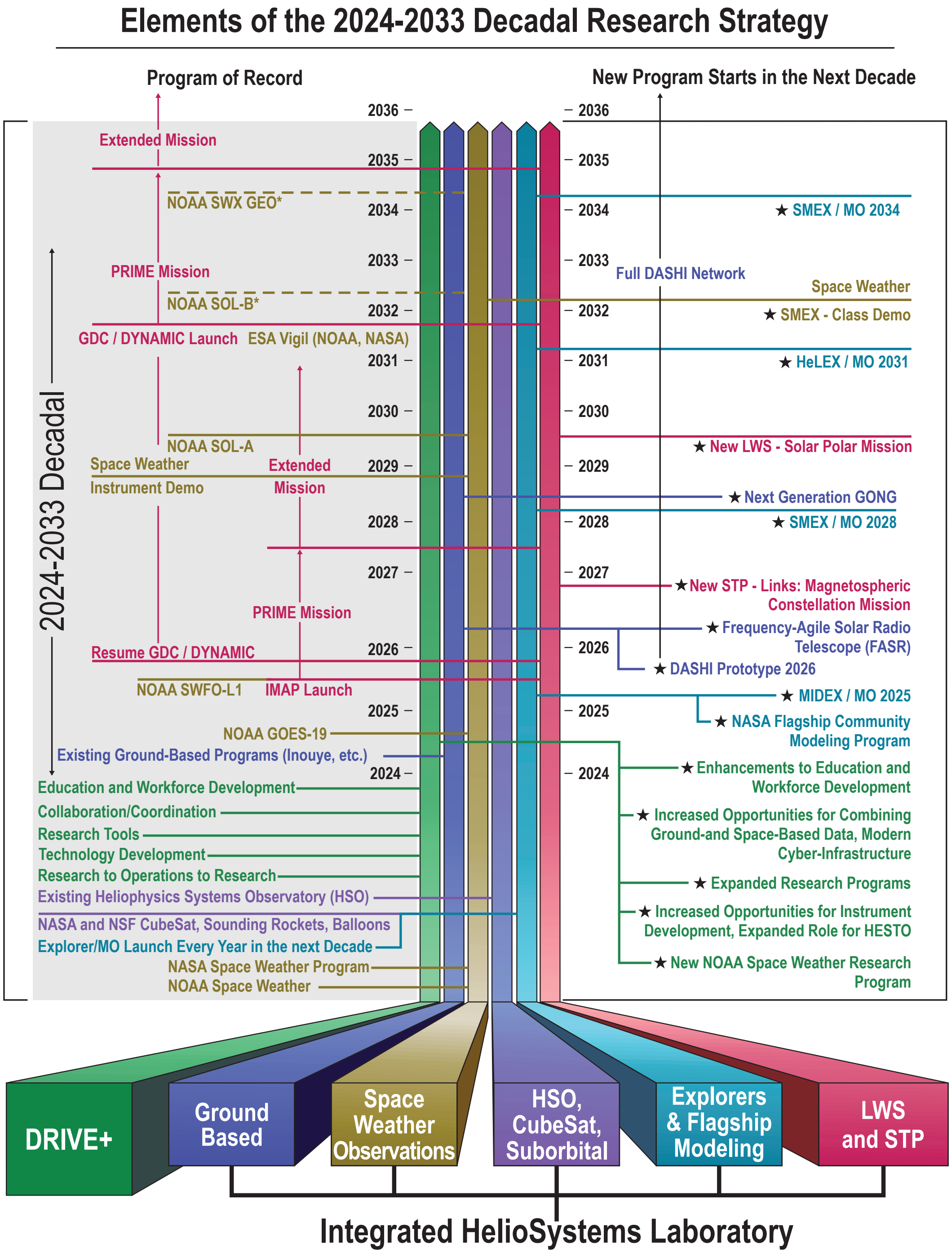

FIGURE S-5 Timeline for realizing the comprehensive and balanced research strategy, including the integrated HelioSystems Laboratory (HSL) and DRIVE+. The elements of the HSL include the complete range of NASA, NOAA, NSF, and relevant AFOSR ground-based projects, space weather observations, the existing NASA Heliophysics System Observatory (HSO), CubeSat and suborbital programs, Explorers, a flagship-level Heliophysics Community Modeling program and new Living With a Star (LWS) and Solar Terrestrial Probe (STP) missions. DRIVE+ includes enhancements in four focus areas: workforce, coordination/collaboration, research tools, and technology development. The programs of record for the agencies are shown on the timeline to the left, and the recommended new program elements for the next decade are shown on the right.
NOTES: Acronyms provided in Appendix H. This figure was modified after release of the report to correct the NOAA space weather program of record.
SOURCE: Created by AJ Galaviz III, Southwest Research Institute.

because it prioritizes specific research focus areas where significant progress will be made over the next decade. The technology exists or requires minimal investment for the recommended missions and projects in the next decade. The enhancements in DRIVE+ build on the significant achievements in the previous decade. If sufficient resources are provided, the entire research strategy can be accomplished in the next decade.

S.4.1 An Integrated HelioSystems Laboratory

This decadal survey introduces the concept of an integrated HSL to describe all the missions, projects, and program elements that generate the data sets (from both observations and large-scale community models) needed to expand the frontiers of solar and space physics, enabling significant progress across the science and space weather themes. The integrated HSL is the means by which the solar and space physics community observes and probes the local cosmos. The HSL is called a laboratory in the broadest sense of the term because it encompasses all assets that generate diverse, inhomogeneous data sets. The HSL highlights the need for a new level of coordination between agencies and within the scientific community to obtain the data necessary for progress on science and space weather (Figure S-3 and Figure S-4). Recommended new components of the integrated HSL for the next decade are shown in timeline form in Figure S-5 and include the following:

- *Two new discovery-enabling NASA missions*. The first is a Solar Terrestrial Probes (STP) mission that is a ground-breaking combination of an in situ constellation and a pair of imaging spacecraft. This mission leverages developments in the satellite industry to enable the large constellation of satellites needed to provide definitive answers to long-standing questions on global solar wind energy entry on the day side of the magnetosphere, and subsequent energy transport through the night side of the magnetosphere to the aurora and regions of large-scale currents. Further, this mission determines the impacts that "intermediate-scale" or meso-scale processes have on the larger-scale evolution of the system. The second is an exploratory LWS mission that, for the first time, resolves the magnetic fields in the polar regions of the Sun. The measurements provided by this mission are critical for understanding the origin of the solar magnetic dynamo and how the magnetic field drives solar activity and shapes the heliosphere over the course of the solar cycle. Understanding the polar fields and velocity structures is also a key factor in predicting space weather approaching Earth. The spacecraft's vantage point enables comprehensive study of the creation and structuring of the solar corona and solar wind.
- *A new NSF Major Research Equipment and Facilities Construction (MREFC) project and two new NSF Mid-scale Research Infrastructure (MSRI) projects*. The Next Generation Global Oscillations Network Group (ngGONG) is an enhanced successor to the highly successful National Solar Observatory GONG network and is the highest-priority MREFC concept. This comprehensive ground-based network is the first to include operational space weather requirements from its conception. The highest-priority, ground-based, mid-scale projects are a MSRI-1 observing system simulation experiment (OSSE) study, a prototype development of the Distributed Arrays of Small Heterogeneous Instruments (DASHI) concept, and an MSRI-2 implementation of the Frequency Agile Solar Radiotelescope (FASR) concept. Together, these critical mid-scale projects serve the entire solar and space physics community facilitating important ionosphere–thermosphere–mesosphere, magnetospheric, and solar and heliospheric science.
- *A flagship-level community science modeling program*. This modeling program has the capacity to solve solar and space physics problems that have broad community interest and that require complex community models. It addresses challenges and opportunities associated with the increasing physical complexity of models, the emerging paradigm of model-data fusion, advances in artificial intelligence, and the rapidly developing high-performance computing landscape. This program provides the sustained infrastructure necessary for model development, maintenance, and broad-based use, as well as training, hiring, and retaining a new interdisciplinary workforce.
- *An enhanced coordinated, multiagency space weather research and operations program*. This program includes an extensive pipeline of demonstration instruments, missions, and projects that feed future space weather operational missions. This pipeline includes a possible stand-alone space weather demonstration

mission developed and operated by the NASA Heliophysics Space Weather Program and extensive integration of NOAA mission observations into the HSL. These two examples demonstrate the strong research to operations to research (R2O2R) of the HSL.

The HSL would be a strategically managed, space-based and ground-based laboratory that includes the new elements discussed above as well as major contributions from missions in development and missions and projects already in operation. Of the strategic missions in development, the Interstellar Mapping and Acceleration Probe (IMAP) mission, to be launched in 2025, provides important links between the inner heliosphere (inside 1 AU), the outer heliosphere, and the very local interstellar medium (beyond 100 AU). The Geospace Dynamics Constellation (GDC) and Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC) missions, with targeted launch dates in 2031, provide critical ITM basic and applied science and space weather observations and help fill a significant gap in ITM space-based observations. They also act as a pathfinder for future heterogeneous constellation missions, ushering in a new era of constellation analysis and science that requires a new paradigm for combining observations, modeling, and theory. Nine small- and medium-class missions (e.g., Explorers) are in various stages of development and are expected to launch in the next decade. The HSL would include existing ground-based facilities, such as the newly commissioned Daniel K. Inouye Solar Telescope, both within the United States and managed by partners abroad.

The HSL assets need to be managed and operated in a coordinated fashion to obtain the joint observations required to address the science of the next decade. The combination of ground-based, space-based, and modeling data is critical for advancing solar and space physics research. This requires increased cooperation between agencies and with international partners, community input, and planning and development of new tools and standards.

- *A vibrant, balanced Heliophysics Explorer program*. Explorer missions and missions of opportunity with a broad range of cost caps are solicited at a 2- to 3-year cadence. Highly targeted missions of opportunity occur for every Explorer opportunity, and smaller, targeted Small Explorers (SMEX) missions occur twice as frequently as the larger missions. To fill a mission cost gap between the Medium-Class Explorers (MIDEX) and strategic missions, a new Heliophysics Large Explorer (HeLEX) class mission is introduced with the first solicitation occurring in 2031.

Beyond the Heliophysics Division of NASA, there are important opportunities for major scientific discoveries via NASA missions that cross divisional boundaries, such as Uranus Orbiter Probe, Escape and Plasma Acceleration and Dynamics Explorers (ESCAPADE) to Mars, and heliospheric measurements by planetary missions on their way to planetary targets. Furthermore, many human exploration missions rely on space weather prediction and mitigation of health risks owing to radiation. Research strategies extend across divisional boundaries and involve coordination at the agency level.

S.4.2 DRIVE+: Enhancements in Research and Technology Programs

Research and technology programs are the backbone of the research strategy, essential for realizing the scientific potential of investments in spaceflight and ground-based projects. While the HSL would provide the coordinated data needed to pursue the ambitious goals of the coming decade, these data must be analyzed, combined with theory, and turned into scientific results. The 2013 decadal survey took an important step toward integrating research programs by introducing the original Diversify, Realize, Integrate, Venture, Educate (DRIVE) initiative, a long-term framework for organizing and enhancing agency research programs that reflects the need for interagency cooperation. The recommended research strategy transforms DRIVE into DRIVE+ (Figure S-6) and includes recommended enhancements in supporting research and technology programs that are essential for realizing ambitious scientific progress. DRIVE+ works with the HSL, turning HSL data into scientific results. DRIVE+ includes both new initiatives and specific enhancements to existing program elements in four areas: workforce, collaboration/coordination, research tools, and technology development, some of which are listed in Figure S-6. They are responsive to existing challenges and reflect emerging developments and opportunities.

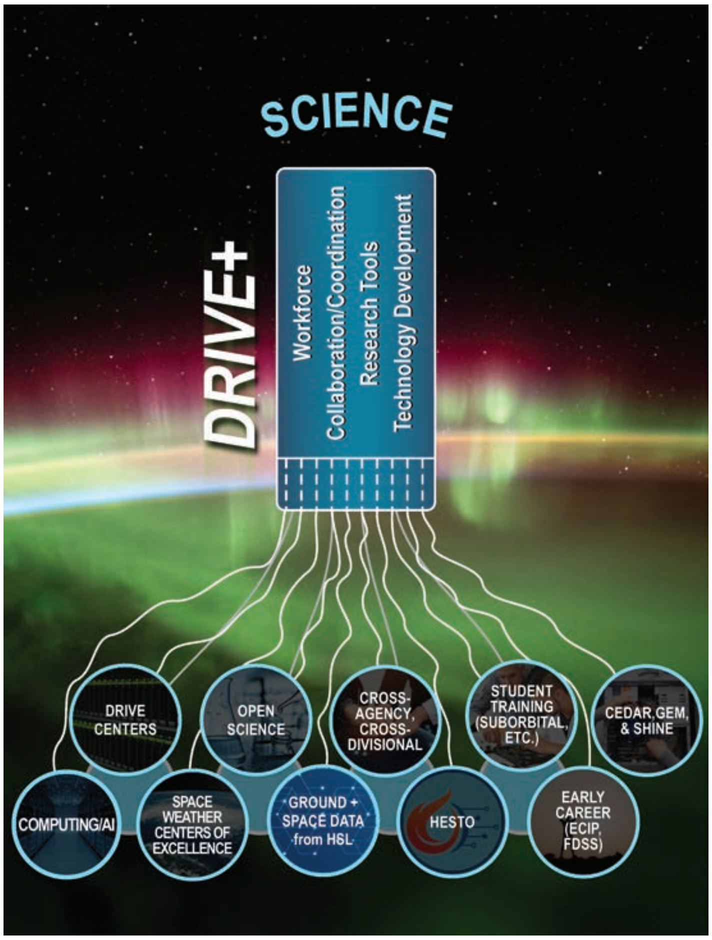

FIGURE S-6 DRIVE+ includes new initiatives and enhancements to existing program elements in four focus areas: workforce, integration, research support, and technology.
NOTE: AI, artificial intelligence; CEDAR, Coupling, Energetics, and Dynamics of Atmospheric Regions; ECIP, Early Career Investigator Program (NASA); FDSS, Faculty Development in GeoSpace Science program (NSF); GEM, Geospace Environment Modeling; HESTO, Heliophysics Strategic Technology Office; HSL, HelioSystems Laboratory; SHINE, Solar, Heliospheric and Interplanetary Environment.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Background image from NASA; Inset circle images: Drive Centers from ©Pixza/Adobe Stock; Open Science from ©totojang1977/Adobe Stock; Cross Agency/Cross Divisional from ©Yingyaipumi/Adobe Stock; Student Training from ©goodluz/Adobe Stock; Cedar, Gem, & Shine from ©AnnaStills/Adobe Stock; Computing/AI from ©frender/Adobe Stock; Space Weather Centers of Excellence from ©Artsiom P/Adobe Stock; Ground Space Data from HSL from ©Windawake/Adobe Stock; HESTO from NASA; Early Career from ©sutadimages/Adobe Stock.

Programs that improve the health and vitality of the profession and prepare the next generation of solar and space physics leaders are essential for sustaining progress. Recruitment and retention of a diverse workforce with a broad range of skills and expertise requires exposure to solar and space physics early in students' academic careers and programs that support research opportunities and training workshops. Experimental opportunities are provided through robust suborbital and CubeSat programs. University faculty are best positioned to broaden the reach of space science in education and provide focused training to students already engaged in the space sciences, thus opportunities to expand the solar and space physics faculty are needed.

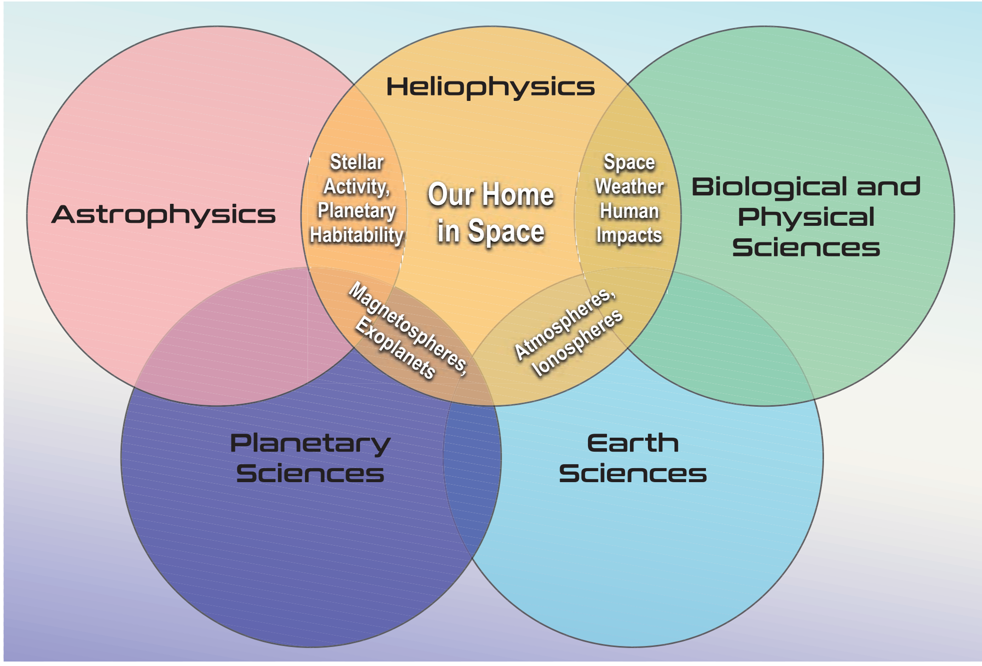

FIGURE S-7 Transformative research is often found at the boundaries between disciplines. Shown here are research areas found at the intersection of the different divisions within NASA's Science Mission Directorate. The solar and space physics community is well positioned to tackle emerging problems and the most pressing national needs.
SOURCE: Created by AJ Galaviz III, Southwest Research Institute.

Although some progress has been made toward increasing women's representation in solar and space physics, they remain underrepresented in comparison to other space science disciplines. The representation of ethnic minorities remains concerningly low. Increased awareness and identification of barriers for historically marginalized identities in science, technology, engineering, and mathematics (STEM) working within the field is needed. To promote change, researchers need increased support to better integrate DEIA+ into research activities and to fully leverage existing agency efforts.

DRIVE+ emphasizes increased coordination and cooperation between and within agencies. Data analysis that combines ground- and space-based observations is essential for scientific advances in solar and space physics. Coordination between federal agencies (NASA, NSF, NOAA, and AFOSR) is needed to enable data access and sharing of tools in a seamless and efficient way. To support this need and to make progress toward open-science goals, continued development of modern cyberinfrastructure[3] will enable effective sharing and utilization of heterogeneous data produced across the integrated HSL. The increasing focus on understanding planetary habitability, Earth's atmosphere, and climate motivates new opportunities for cross-divisional collaboration (Figure S-7).

Implementation of DRIVE+ will ensure robust and sustainable research programs through targeted investments. DRIVE+ ensures that the community has the resources it needs to best utilize data from past and currently operating missions and facilities. It also strengthens theory and modeling (T&M), ensuring support for a range of project scales. DRIVE+ supports small-scale theory and modeling efforts through grant programs whereby small groups of researchers tackle targeted problems. These efforts infuse knowledge into larger-scale models that are developed by larger teams through programs like NASA DRIVE Centers. This hierarchy ultimately enables

[3] "The hardware, software, networks, data and people that underpin today's advanced information technology." See https://new.nsf.gov/focus-areas/cyberinfrastructure.

development of flagship-level *community* models that address the most challenging solar and space physics problems. The community models are incorporated into the integrated HSL as a resource for the community to obtain modeling data.

DRIVE+ also invigorates technology and workforce development programs that inject new capabilities and new ideas into the field. The rapid expansion of the commercial space sector, along with increased capabilities and availability of small satellite technologies, provides new opportunities for solar and space physics. Large satellite constellations for science are within reach and enable the multipoint measurements needed to understand the Sun–Earth–space system of systems that is humanity's home. This requires the development of a new capability to efficiently build and calibrate hundreds of identical copies of scientific space instrumentation.

S.4.3 Preparation for the Next Decade and Beyond

An important element of the research strategy is preparation for the next decade and beyond. Small-scale Heliophysics technology programs such as Heliophysics Flight Opportunities for Research and Technology (H-FORT) and Heliophysics Instrument Development for Science (HTIDeS) provide opportunities to develop and mature instruments up to a certain level. More complex technologies and maturation to the level required for flagship strategic missions require larger investment. In some cases, future mission needs are shared across divisions within NASA's SMD (such as missions to Uranus or interstellar space) and call for investment and coordination at the SMD level.

Preparation for beyond the next decade is not limited to hardware. Interagency, intra-agency, and international partnerships pave the way for implementation of future ambitious projects. Transformative research is often found at the boundaries between disciplines (Figure S-7). The solar and space physics community is well positioned to tackle emerging problems at these boundaries, and the most pressing national needs, such as space weather on the Moon and Mars. Increased coordination within the agencies is needed to capitalize on the solar and space physics expertise that has resulted from decades of investment.

S.4.4 Challenges and Opportunities

This comprehensive research strategy calls for increased agency budgets that are commensurate with the ambitious science and space weather themes for the next decade. Any progress toward the priority science themes and guiding questions (Chapter 2) requires a budget increase from fiscal year (FY) 2024 levels. In addition, without enhanced resources, the recommended strategy would be seriously imbalanced, because there would be no new LWS or STP missions, and only one of the highest-priority STP and LWS missions from the previous decade (IMAP) would be launched. In particular, the current budget does not support completion of the program of record, most notably Geospace Dynamics Constellation (GDC) and Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC), two high-priority missions recommended in the 2013 decadal survey. The decadal survey committee acknowledges the significant progress in the development of GDC and strongly affirms the value of GDC science and the importance of this mission in advancing understanding and prediction of space weather. Without new missions, the imbalanced program and resulting lack of scientific progress would be devastating to the solar and space physics community. Furthermore, the lack of progress could be devastating to society, because it would inhibit progress on space weather prediction and mitigation. Increased reliance on space-based assets, increased vulnerability of ground-based infrastructure, and humanity's venture beyond low Earth orbit make space weather research of paramount importance in the next decade.

The proposed research strategy is ambitious but also realistic (Table S-2). With a balance across mission and project size, cadence, subdiscipline science, institute size, and career stage, the research strategy broadly encompasses solar and space physics. The strategy integrates science and space weather, with realistically achievable space weather outcomes in the next decade. The recommendations include prioritized missions and ground-based projects, and implementation of the research strategy within NASA is further prioritized through decision rules (see Chapter 6). With sufficient resources, this balanced strategy is attainable and would make the next decade the golden age of discovery and understanding of our local cosmos and humanity's place in it.

S.5 SUMMARY OF RECOMMENDATION TOPICS

TABLE S-2 Recommendation Topics in Order of Appearance in the Report, Agencies, and Cross-Reference Sections for the Research Strategy

Recommendation Topic	Agency	Cross-Reference (Section)
Space Weather		
3-1 Foundation-wide strategic space weather plan	NSF	3.3.1
3-2 Space weather user surveys to set priority research goals	NOAA, AFOSR	3.3.2
3-3 Space weather research targeted to prioritized goals	NASA, NSF	3.3.3
3-4 Space weather research program and predictive models	NOAA, AFOSR	3.3.4
3-5 Space Weather Program growth to support space weather demonstration missions	NASA	3.3.5
3-6 Space weather mission enhancements	NASA	3.3.5
3-7 New data streams for operational services	NOAA	3.3.5
State of the Profession		
4-1 Fund demographic data collection	NASA, NSF, NOAA	4.2.1
4-2 Expand definition of broader and broadening impacts	NASA, NSF	4.3.1
4-3 Faculty Development in geoSpace Sciences (FDSS)	NSF	4.3.2
4-4 Expanding the reach of space science in education	All	4.3.2
4-5 Enhancing DEIA+	All	4.4.2
4-6 Increase public outreach and citizen science programs	All	4.5.2
Integrated HelioSystems Laboratory		
5-1 Manage all assets as part of an integrated HelioSystems Laboratory	NASA, NSF, NOAA	5.2.1
5-2 Mid-scale Research Infrastructure (MSRI)	NSF	5.2.2
5-3 Major Research Equipment and Facilities Construction (MREFC)	NSF	5.2.2
5-4 Flagship-level Community Science Modeling Program	NASA	5.2.2
5-5 Review of CubeSat programs	NASA, NSF	5.2.3
5-6 Suborbital to Mission of Opportunity cost and risk gap	NASA	5.2.3
5-7 Heliophysics Explorer Missions	NASA	5.2.3
5-8 Solar Terrestrial Probes Program	NASA	5.2.3
5-9 Living With a Star Program	NASA	5.2.3
DRIVE+		
5-10 Research that combines ground- and space-based observations	NASA, NSF	5.3.2
5-11 Cyberinfrastructure development	NASA, NSF, NOAA, AFOSR	5.3.2
5-12 Cross-disciplinary research	NASA, NSF	5.3.2
5-13 NSF organizational structure review	NSF	5.3.2
5-14 Funding for infrastructure missions to validate data	NASA	5.3.3
5-15 Support for analysis of archival data	NASA	5.3.3
5-16 Augmentation of Heliophysics Research Program	NASA	5.3.3
5-17 Theory and modeling for strategic missions	NASA	5.3.3
5-18 Review the structure of DRIVE Centers and Space Weather Centers of Excellence	NASA	5.3.3
5-19 Instrument development	NASA	5.3.4
Preparations for Beyond the Decade		
5-20 Cross-divisional approach for future projects and programs	NASA	5.4.4
Decision Rules		
6-1 Decision rules for the recommended program	NASA	6.2.4

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Solar and Space Physics

The Space Age began a little more than 65 years ago and with it came the birth of a new science, space physics. However, the foundations of modern space physics harken back to 19th century studies of the aurora, sunspots on the Sun's surface and atmosphere, and the discovery of the hot solar corona. Realizing the interconnected nature of these regions, a community began to coalesce and describe themselves as solar and space physicists. With the earliest spacecraft, the upper atmosphere (the ionosphere and thermosphere) was explored and this exploration was extended to what became known as the low Earth orbit environment, and then to Earth's radiation belts and magnetosphere. This followed investigations from the 19th century applying the ideas of electromagnetism to Earth's magnetic field, giving rise to the science of geomagnetism and its extensions into the upper atmosphere, and to the aurora, thereby laying the foundations for magnetospheric physics, the study of the solar wind and its interaction with Earth, and the subsequent development of space plasma physics.

The hunger for humanity to explore more challenging regions, farther from and closer to the Sun, introduced a broader description of the science that now embraced the entire heliosphere. Heliophysics comprises the study of physical process from deep in the solar interior, to the corona and solar wind; from the solar wind to its impact and influence on Earth, planetary, and minor bodies; and to its influence on the outmost reaches of the solar system as it collides with the interstellar medium. This encompasses an enormous region extending three times farther than the orbit of Pluto in the "upwind" direction (the direction in which the Sun and solar system moves through the Milky Way), and tens of thousands of times farther than Earth is from the Sun in the opposite direction. In the past decade, the field has expanded even beyond these boundaries. There are now spacecraft exploring and making measurements of fields and particles in interstellar space, the environment between the stars that surrounds the heliosphere, contributing in a novel and unique way to furthering the knowledge of the interstellar medium. The knowledge and expertise of the dynamical interplanetary medium and its impact on and interaction with planets, moons, and other solar system bodies is now being applied to the study of exoplanets. Not only is planetary exploration extending far beyond the solar system, but knowledge about the effects of the "weather" created by the Sun is being utilized to inform the "weather" experienced by exoplanets orbiting distant stars.

Thus, the constantly evolving and expanding science of solar and space physics is no longer bound by the heliosphere. The accomplishments are now fertilizing new fields that are well beyond these boundaries. This extension is driven by the knowledge and expertise in solar and space science.

1.1 SCIENCE HIGHLIGHTS FROM THE PAST DECADE

1.1.1 Introduction

The past decade witnessed history-making explorations of the heliosphere as humanity touched the Sun and explored in situ the interstellar medium surrounding the protective bubble, the heliosphere, encompassing both the closest and farthest excursions from the Sun. Following studies of the Sun since the dawn of humanity with increasingly sophisticated observatories, the most capable and powerful solar observatory, the Daniel K. Inouye Solar Telescope, experienced first light in 2019, promising to revolutionize ground-based solar physics. The epochal discoveries and the opportunities the space- and ground-based missions herald for the forthcoming decade fall under several themes outlined below.

Through exploration of our local cosmos, the discoveries, theories, and models have revealed that dynamical processes driven by the Sun and surrounding interstellar environment shape the habitability of the modern day Earth, its technologies, and peoples. Over the past decade, discoveries and efforts to project future changes in the space environment, now recognized as space weather, have helped safeguard the socioeconomic and security infrastructures. The increasing reliance on technology in the future will bring even greater challenges in safeguarding the habitability of Earth and the integrity of humanity's technologies and human exploration.

A selected set of highlights from the past decade (Figure 1-1) are presented here. These highlights scarcely do justice to the full gamut of the remarkable and exciting discoveries and progress made by solar and space scientists over the past 10 years. However, these highlights were selected to exemplify the nature of the science and the directions the field is anticipated to take in the next decade.

1.1.2 Touching the Sun

At 09:33 UT on April 28, 2021, the National Aeronautics and Space Administration (NASA) Parker Solar Probe (PSP) touched the atmosphere of the Sun, an extraordinarily hostile and entirely new, unexplored region of space (Figure 1-2). The solar atmosphere extending above the surface is bound to the Sun, unlike the supersonic solar wind that has escaped the Sun's gravitational pull. The boundary of the solar atmosphere delineates the region where plasma signals ("Alfvén waves") propagate back to the surface from the region outside that is completely detached from its solar origin. In crossing that boundary, PSP has become the first and only human-built spacecraft to touch the Sun. This stunning technological and scientific achievement helps provide the keys to unlocking the secrets of how the solar atmosphere is heated to million-degree temperatures, thousands of times higher than those measured at the surface. Moreover, the in situ measurement of the solar wind slowly separating from the atmosphere is one of the greatest heliospheric achievements ever made. A combination of in situ measurements made by PSP while enduring thousand-degree temperatures so close to the Sun and remote observations by the European Space Agency (ESA) Solar Orbiter mission revealed an extremely turbulent atmosphere, with fluctuations caused by the release of magnetic energy on small scales through a "magnetic reconnection" process. In the next decade, these observations position solar and space physics to answer the 70-year-old questions of how the solar corona is heated and how the solar wind is accelerated, as well as stimulate theoretical explanations and models for the role of turbulence in the heating and acceleration processes.

1.1.3 Capturing the Heart of Magnetic Explosions in Space

For less than 100 milliseconds on October 16, 2015, the four NASA Magnetospheric Multiscale (MMS) spacecraft flew through a magnetic reconnection event at the boundary where the Sun's magnetic field pushed against Earth's magnetic field (Figure 1-3). In this short instant of time, instruments on MMS captured, for the first time, the precise process that causes magnetic field lines to snap and reconnect in a new configuration, which results in magnetic explosions that catapult electrons to speeds up to hundreds of thousands of kilometers per second.

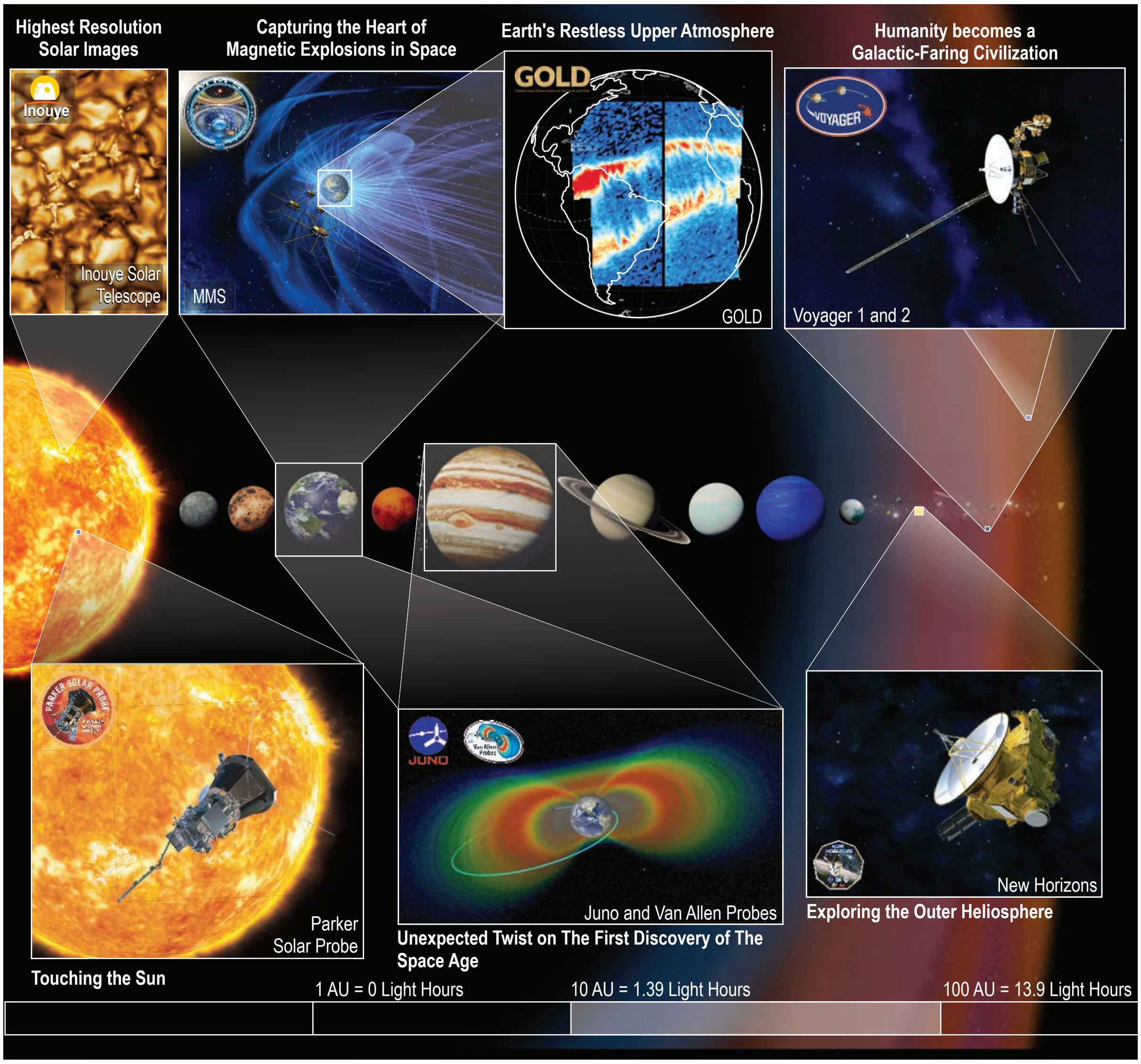

FIGURE 1-1 Log plot of heliocentric distance and propagation times to Earth showing the spacecraft and missions that highlight some of the scientific achievements of the past decade: Parker Solar Probe touching the Sun; Magnetospheric Multiscale (MMS) mission exploring the plasma physics of explosive magnetic reconnection; Van Allen Probes discovery of a third Van Allen radiation belt and Juno spacecraft first exploration of Jupiter's polar region; GOLD (Global-Scale Observations of the Limb and Disk) discovery of upper atmosphere plasma bubbles; and New Horizons revealing how the outer heliosphere is shaped by pickup ions of interstellar origin. Last, the past decade demarcates when humanity became a galactic-faring civilization with Voyager 1 and 2 crossing the heliopause and entering interstellar space.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; (*background*) Keck Institute for Space Studies/Chuck Carter; (*Inouye Solar Telescope*) NSO/NSF/AURA, https://nso.edu/telescopes/dkist/first-light-cropped-image. CC BY 4.0; (*background simulation with MMS*) NASA; (*GOLD observations*) Eastes et al. (2019), https://doi.org/10.1029/2019GL084199. CC BY 4.0; (*Juno and Van Allen Probes*) NASA/Goddard Space Flight Center Scientific Visualization Studio https://svs.gsfc.nasa.gov/3951; (*Voyager spacecraft*) NASA/JPL; (*New Horizons Spacecraft*) NASA/Johns Hopkins APL/SwRI/Steve Gribben; (*Parker Solar Probe*) NASA's Scientific Visualization Studio and Johns Hopkins University Applied Physics Laboratory.

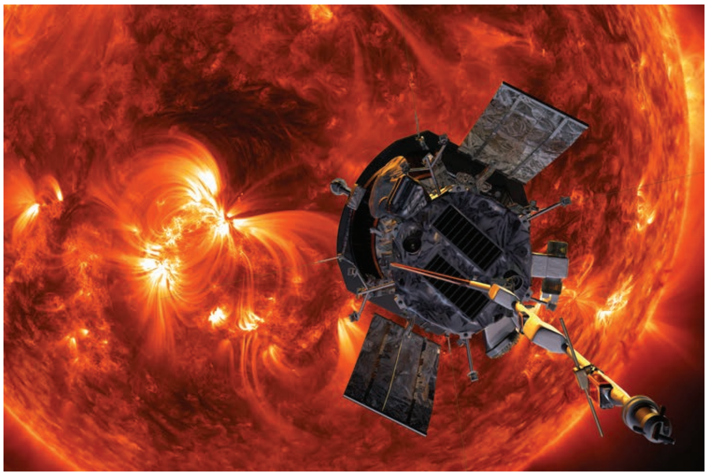

FIGURE 1-2 Parker Solar Probe (PSP) viewing the source region of the fast solar wind.
SOURCE: NASA/Johns Hopkins APL/Steve Gribben.

Takeaways: The use of multiple spacecraft and multiple-instrument suites that combine remote and in situ observations holds the key to unlocking the secrets that the Sun and the heliosphere still hold. For example, the Parker Solar Probe mission (1) demonstrated the ability to explore unimaginably challenging environments and (2) enables combined multispacecraft in situ and remote observations (and soon ground-based observations with the Inouye Solar Telescope) to identify the small-scale magnetic-related phenomena that release the energy that may be responsible for heating the corona and driving the solar wind.

Magnetic reconnection is a universal process, driving energetic phenomena in extreme environments such as black holes, neutron stars, and the Sun and other stars. Closer to home, it is reconnection that allows solar wind to breach Earth's magnetic shield, leading to violent space storms and high levels of energetic particle radiation. The MMS mission was designed to use Earth's magnetosphere as a natural laboratory to perform definitive experiments on reconnection. The four spacecraft, each carrying 25 instruments capable of making measurements 100 times faster than previously possible, have yielded the first fully three-dimensional (3D) pictures showing how the highly dynamical magnetic fields suddenly break, and how the electrons and ions are accelerated in the process. The precision and speed of the MMS measurements is effectively a "microscope" in space that enables visualization of the highly localized processes. This discovery of the fundamental processes governing reconnection is a giant leap in the understanding of what triggers such magnetic explosions throughout the universe. The use of advanced theory and numerical simulations played a critical role in this discovery by predicting key signatures of the reconnection triggering process. Over the next decade (2024–2033), theory and modeling will continue to be an essential guide to the highly complex and turbulent reconnection environment. MMS observations have spurred major efforts to reconcile theory and observations by incorporating the very detailed physical processes of electrons and ions in large-scale simulations, which will motivate new theories for particle energization and acceleration via reconnection- and turbulence-related mechanisms well into the next decade.

1.1.4 An Unexpected Twist on the First Discovery of the Space Age

With the launch of the NASA Van Allen Probes twin spacecraft mission into the radiation belts in late 2012, the expectation was that the mission would probe the dynamics of the two rings of high-energy particles circling Earth originally discovered by James Van Allen and the first U.S. space mission in 1958. Instead, and most unexpectedly, not two but three distinct rings were observed. This discovery underlines the exploratory nature

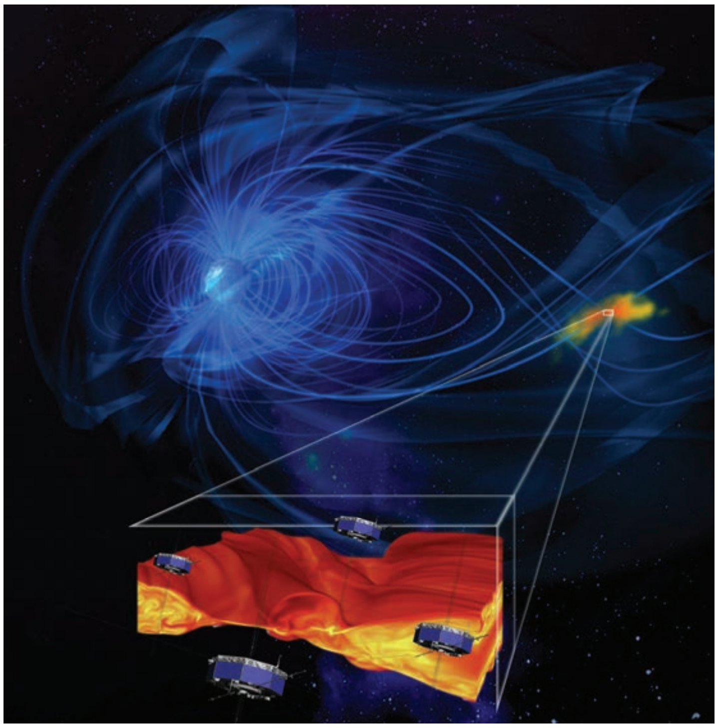

FIGURE 1-3 Schematic of a reconnection event observed in Earth's magnetotail by NASA's Magnetospheric Multiscale (MMS) spacecraft. Overlaid is a simulation of the turbulent layer underlying the reconnection event on the new dynamical and spatial scales enabled by the MMS instrumentation. These MMS observations at the smallest scales emphasize the need to combine this detailed knowledge with future larger-scale observations to investigate the global consequences of magnetic reconnection. Understanding the cross-scale nature of this process helps better predict extreme events in the space environment and helps protect spacecraft and astronauts as regions increasingly distant from Earth are explored.
SOURCES: (*spacecraft*) Cudmore (2015); (*background image*) NASA Goddard's Conceptual Image Lab.

Takeaways: (1) The past decade has demonstrated the importance of multispacecraft, multipoint measurements in identifying fundamental physics of multiscale spatial and temporal processes. (2) MMS provides a compelling rationale for multipoint measurements, effectively creating a laboratory in space, if transformative progress is to be made in understanding the building blocks of a highly coupled complex multiscale heliospheric system.

and state of space science today, with each new mission unraveling previously unknown physical processes and phenomena (Figure 1-4).

The radiation belts are highly dynamic, at times changing in shape and intensity within hours. Earth's radiation belts typically comprise the inner belt closer to Earth, which is mainly composed of energetic protons, and the outer belt farther from Earth, which is dominated by high-energy "killer" electrons that are especially hazardous for spacecraft and their subsystems. In late 2012, the radiation belts were assaulted by an intense geomagnetic storm that created the third belt between the two preexisting ones. The third belt persisted for 4 weeks before a powerful interplanetary shock wave from the Sun annihilated it, returning the Van Allen belts to their standard two-belt configuration.

Besides profoundly affecting Earth's radiation belts, space storms can dump large numbers of radiation belt particles into Earth's upper atmosphere, thereby depleting the belts and destroying atmospheric ozone. Suborbital and CubeSat missions, such as the Colorado Student Space Weather Experiment (CSSWE), Balloon Array for Radiation-belt Relativistic Electron Losses (BARREL), and Focused Investigations of Relativistic Electron Burst

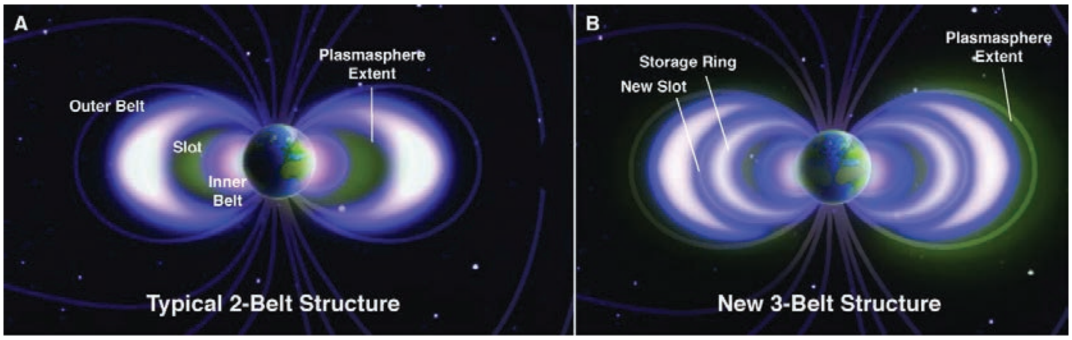

FIGURE 1-4 A long-lived relativistic electron storage ring embedded in Earth's outer Van Allen belt. This structure was created as the result of a strong geomagnetic storm and survived for several weeks before the system returned to the typical two-belt structure. NASA's Van Allen Probes mission was designed to study changes in the radiation belts and the physical processes that drive those changes, particularly those that originate from the dynamical solar wind and its impact on Earth's magnetic field. SOURCE: From D.N. Baker, S.G. Kanekal, V.C. Hoxie, et al., 2013, "A Long-Lived Relativistic Electron Storage Ring Embedded in Earth's Outer Van Allen Belt," *Science* 340(6129):186–190, https://doi.org/10.1126/science.1233518. Reprinted with permission from AAAS.

Takeaways: (1) The Van Allen belts are affected by solar storms and can grow dramatically, thereby disrupting communications and Global Positioning System satellites, as well as posing a danger to humans in space. (2) The 7-year-long Van Allen Probes mission has rewritten the radiation belt science textbooks, the third radiation belt being emblematic of the unexpected new insights returned by the mission into this fascinating region. (3) The Van Allen probes are another example of a laboratory in geospace. (4) International collaborations significantly increase a mission's capabilities, whether by collaborating on the instrumentation suite (provision of instruments, addition of expertise, etc.) or even creating synergies between independent missions, such as occurred between the Japanese Arase mission (formerly known as Exploration of Energization and Radiation in Geospace) and Van Allen Probes to the considerable enrichment of both.

Intensity, Range, and Dynamics (FIREBIRD), provided complementary measurements of this atmospheric loss during the Van Allen Probes mission, illustrating that smaller missions can effectively and strategically augment major missions.

1.1.5 Volcanoes Reaching All the Way to Space

The Hunga-Tonga volcano eruption on January 15, 2022, was a once-in-lifetime event that provided a dramatic example of how the whole Earth, from subsurface to outer space, operates as one coupled system. The vast cloud of water vapor released from the submarine volcano created strong gravity waves in the atmosphere that propagated across the globe and all the way up to the upper atmosphere and its ionized portion, the ionosphere, essentially reaching outer space (Figure 1-5). Such waves create vertical coupling across atmospheric layers in ways that only the next decade with the upcoming Geospace Dynamics Constellation (GDC) mission will be able to resolve.

However, the substantial advances in developing models such as the Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X) allowed, for the first time, a simulation of the entire atmosphere from the surface to low Earth orbit, including the physics of both the neutral atmosphere and the ionosphere. Worldwide observations of the waves provided a key validation of the model during some of the most extreme conditions ever observed. Such coupled simulations not only help reveal the nature of waves generated in the lower atmosphere but also address the longstanding conjecture of understanding the driving mechanisms behind quiet time bubbles/scintillations that pose a significant threat to radiofrequency communication and navigation systems.

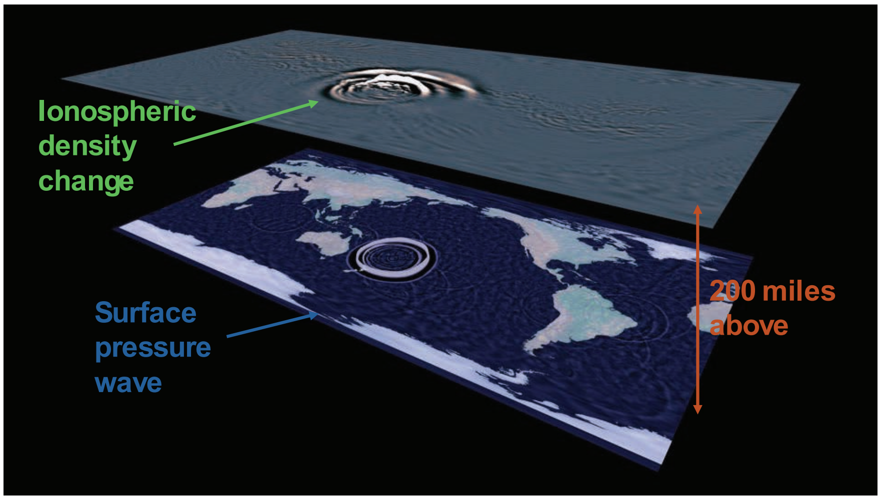

FIGURE 1-5 WACCM-X Community Model simulation reveals the waves emanating from the Hunga-Tonga eruption that reveal how the atmosphere connects to the space environment.
SOURCE: ©2024 UCAR.

Takeaway: Advancements in physics-based models have enabled linking different regions of the atmosphere, treating it as one system from the surface of Earth to the edge of space.

1.1.6 Earth's Restless Upper Atmosphere

Far from being a stable quiescent region, Earth's upper atmosphere is filled with plasma bubbles—stark voids in the charged plasma enveloping Earth—that are especially prominent in the evening hours after sunset. These seemingly harmless structures have proven to be space weather phenomena, as they impact Global Positioning System (GPS) signals traversing from spacecraft above, through the ionosphere, to ground receivers below. Utilizing its birds-eye view from geostationary orbit, NASA's Global-Scale Observations of the Limb and Disk (GOLD) mission has provided a wealth of observations of Earth's thermosphere and ionosphere (Figure 1-6). GOLD's fixed position at geostationary orbit has offered a radically different viewpoint from that seen from low Earth orbit. Its continuous view of these bubbles has resolved ambiguities of their formation and motion. GOLD images combined with data from low Earth–orbiting spacecraft such as the Ionospheric Connection Explorer (ICON), Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC-2), and ESA's Swarm spacecraft have given a valuable demonstration of the power of coordinated multipoint measurements that greatly exceed the value of any single mission alone.

1.1.7 Humanity Becomes a Galactic-Faring Civilization

This past decade witnessed humanity become a galactic-faring civilization. At a distance 120 times greater than that from the Sun to Earth and after 40 year's journey, Voyager 1 and 2 exited the bubble created by the Sun—the heliosphere—to enter interstellar space and give humanity the first glimpse of interstellar plasma, magnetic fields, and unmodulated (i.e., unaffected by the heliosphere) low-energy galactic cosmic rays. This extraordinary event, a mere 65 years after humanity first ventured into interplanetary space, is a triumph of technology and scientific persistence. Virtually every measurement made by the aging instrumentation on board the 1970s vintage Voyager spacecraft represents a profound, and possibly one-of-a-kind, discovery that is unlikely to be replicated for several generations.

At the turn of the past decade, the Interstellar Boundary Explorer (IBEX) probe remote sensing measurements discovered an unexpected "ribbon" of energetic neutral atoms (ENA) originating from the interstellar medium. Analysis of the ribbon and related ENA measurements allowed scientists to derive the strength and direction of the

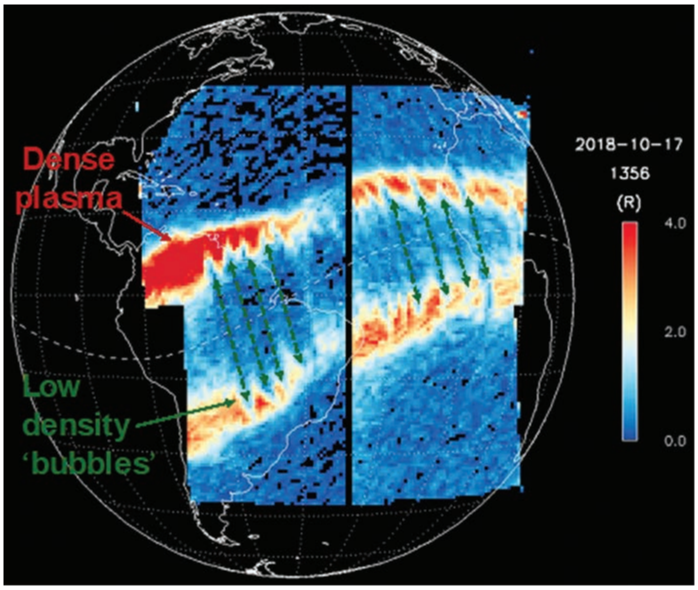

FIGURE 1-6 Global-Scale Observations of the Limb and Disk (GOLD) observations of the ionosphere at nighttime reveals density structures associated with an instability in the plasma. The low-density regions that form are referred to as a plasma bubbles. SOURCE: Eastes et al. (2019), https://doi.org/10.1029/2019GL084199. CC BY 4.0.

Takeaways: (1) Earth's ionosphere–thermosphere–mesosphere system is a highly coupled mixture of neutral gas and charged plasma that surrounds Earth. This region responds strongly to external forces, both from drivers in the lower atmosphere and from the Sun and magnetosphere above. (2) Key scientific advances in the past decade have come from a combination of new observations that exploit new vantage points (such as GOLD) or combine data from multiple observatories.

very local interstellar magnetic field (Figure 1-7) and map the large-scale structure of the heliosphere. The analysis was made possible based on theory and modeling predictions made 25 years ago. The discoveries made by the Voyagers and IBEX spark questions about the fundamental structure of the large-scale heliosphere—its effect on and response to the very local interstellar medium. Ultimately, these measurements provide the key for how these processes contribute to creating a habitable environment for Earth. Combining these observations with theories and models provides knowledge about the interaction of distant stars with their interstellar environments and expands the understanding of habitability throughout the galaxy.

The understanding of very distant regions of the heliosphere and the interface to interstellar space is made possible by the ability to simultaneously use and coordinate remote and in situ measurements. This coordination has accelerated the understanding of the complexity of the coupled heliospheric–interstellar medium system, its underlying dominant physical processes, such as charge exchange, and the complex coupling of heliosphere to the local interstellar medium and vice versa in a way that could not have been anticipated a decade ago.

1.1.8 Heritage from the Dawn of Humanity: First Light from the Inouye Solar Telescope

Solar observatories date to the dawn of agriculture when humanity's earliest farmers began charting the seasons. One of the earliest in the Americas, constructed between 250 and 200 BCE, is the 2,300-year-old archaeological site Chankillo in Peru. Other notable stone circle solar observatories include the 5,000-year-old Stonehenge in England, the 7,000-year-old Goseck Ring in Goseck, Germany, and the world's oldest from more than 7,000 years ago in the Nabta Playa in Egypt.

FIGURE 1-7 Were humans able to view the night sky with eyes capable of observing energetic neutral atoms (ENAs), the largest object observed would the IBEX ribbon arcing across much of the sky. The "ribbon" of enhanced flux in the IBEX ENA sky maps is a remarkably organized structure that is used to infer the strength and direction of the very local interstellar magnetic field. Ultimately, the ribbon is a consequence of the interstellar magnetic field "squeezing" the heliosphere. The discovery and explanation of the ribbon exemplify how the combined use of observations, theory, and simulations yields groundbreaking discoveries of the most distant parts of the heliosphere and beyond.
SOURCE: Composed by AJ Galaviz III, Southwest Research Institute.

Takeaways: (1) The Voyager 1 and 2 interstellar mission epitomizes discovery science, exploring what was once regarded as an unreachable environment. Humankind is unlikely to replicate the Voyager discoveries for several generations without an agency/directorate-wide effort. (2) The simultaneous use and coordination of in situ and remote measurements of these most remote regions by Voyager 1 and 2, New Horizons, and IBEX (and soon IMAP) significantly advanced the field.

In 2019, the National Science Foundation (NSF) commissioned the most advanced solar observatory ever constructed, Inouye. This U.S.-led, NSF-funded, and National Solar Observatory (NSO)-operated telescope promises to revolutionize ground-based solar physics. Its five instruments, four of which are polarimeters, operate over a broad wavelength covering the visible, near-infrared, and mid-infrared spectrum. Thanks to its exceptional site on Haleakala, Hawai'i, a large 4 m aperture primary mirror (Figure 1-8), advanced adaptive optics integrated into the telescope, and numerous design innovations, Inouye can observe features as small as 20 km on the surface of the Sun—an unprecedented level of detail. This unprecedented high-resolution capability enabled the first direct images of locally excited acoustic waves in the solar chromosphere (Bahauddin et al. 2024). Moreover, the state-of-the-art magnetic field measurements of the Sun's chromosphere and corona provided by Inouye will revolutionize our understanding of small-scale magnetic activity, plasma jets at the solar surface, the triggering of solar flares and eruptions, and long-term solar cycle variations of these small-scale structures.

In the next decade, Inouye will not only play a world-leading scientific role as one of the great observatories but will also be a critical element of space- and ground-based multiobservatory, multinational studies of the Sun.

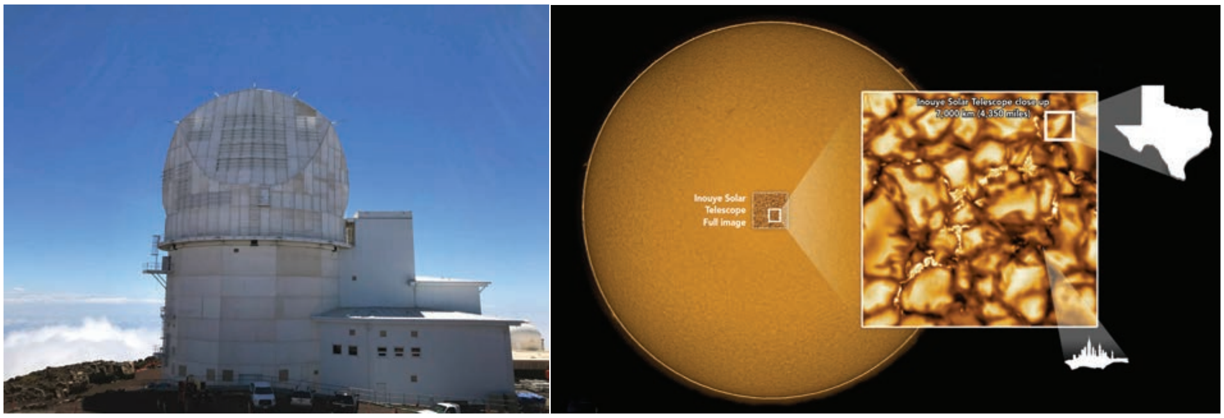

FIGURE 1-8 (*Left*) Daniel K. Inouye Solar Telescope, the world's largest and most powerful solar telescope, is now commissioned and beginning to return scientific data of unprecedented resolution and fidelity. (*Right*) Beginning with its first science observations in February 2022, Inouye is producing the highest resolution images of the Sun's surface ever taken, here showing features as small as 20 km in size (the size of Manhattan Island). The image shows a pattern of turbulent cell-like structures, each the size of Texas, analogous to a "boiling" gas that covers the entire Sun. These violent motions illustrate how heat is transported from within the Sun to its surface.
SOURCES: (*Left*) NSO/NSF/AURA, https://nso.edu/telescopes/dkist/fact-sheets/dkist-overview. CC BY 4.0. (*Right*) NSO/NSF/AURA, https://nso.edu/telescopes/dkist/first-light-context-full-sun. CC BY 4.0.

Takeaways: (1) Ground-based observations are a vital cornerstone of solar physics, with capabilities unavailable to space-based observations. (2) Inouye was enabled by a broad partnership that included international partners. (3) Inouye will play a central role in multiobservatory studies of solar phenomena and is already making joint observations with the Parker Solar Probe.

1.1.9 Making Sense of the Unimaginably Vast and Complex

How does one make sense of a region so vast that begins at the surface of the Sun and extends nearly 25 billion kilometers into the void of space? It takes some 22 hours and 35 minutes for radio waves sent from Earth, traveling at the speed of light, to reach Voyager 1. And yet shock waves driven from the Sun's active surface are observed by Voyager 1 years later. Over such unimaginably vast distances, the complex physics that connects these disparate regions is only captured by the most advanced computer models using the largest supercomputers. As illustrated in Figure 1-9, models and theory capture the physics and the extraordinary complexity of the temporal 3D bubble, the heliosphere, in which humanity resides. Spacecraft provide snapshots of a miniscule region of space at different times and yet these sparse observations provide important input for model boundary conditions and model validation.

These models and theory also connect and couple the very large to the very small, as in Figure 1-10. The struggle to understand the global scale with highly localized spacecraft observations is also a struggle to connect large-scale phenomena, such as a magnificent auroral display, to the solar drivers and the microscopic kinetic processes responsible for creating the other-worldly shifting radiance of the northern lights. However, with tremendous progress in the past decade, theory and modeling—as illustrated in Figure 1-10—now couples shock waves and plasma eruptions at the Sun to a highly disturbed magnetosphere about Earth and the subsequent magnificence of a highly structured auroral display that encompasses the northern (and southern) latitudes.

This progress notwithstanding, theory and modeling promise so much more in the coming decade, moving toward the level of completeness and self-consistency in the models that will extract the full feedback and response to the inclusion of the full range of spatial, temporal, continuum, and kinetic scales. Modeling will provide both perception and understanding of the local cosmos, from which will emerge the capability of predictive operational models capable of serving the growing needs of humanity's technological society.

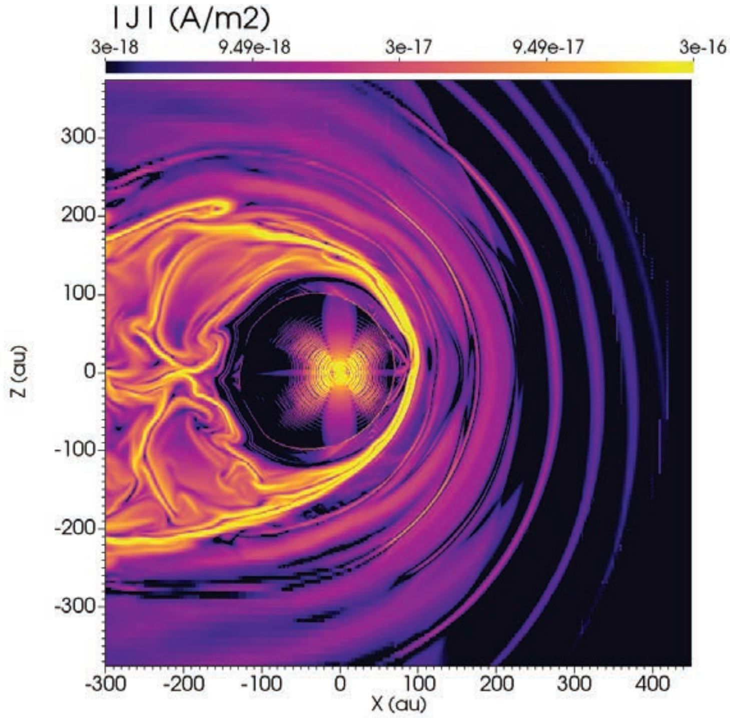

FIGURE 1-9 In this model of the entire heliosphere, the color shows the current density (in A/m^2). The bright yellow center encompasses the Sun from which the solar wind emanates and expands, creating a vast bubble in interstellar space bounded by heliospheric termination shock and a heliopause (the brightly colored yellow surface) that separate solar and interplanetary material. Shock waves driven from the Sun cause the entire heliospheric bubble to shake and oscillate. Transmitted interplanetary shock waves create an equally disturbed, dynamical, and turbulent very local interstellar medium.
SOURCE: F. Fraternale and N.V. Pogorelov, ISSI Team 23-574, "Shocks, Waves, Turbulence, and Suprathermal Electrons in the Very Local Interstellar Medium," Presented at the AGU Fall Meeting 2023 (Poster SH51D-2652).

Global models of the large-scale heliosphere (Figure 1-9) and the geospace system (Figure 1-10) have seen tremendous growth in the past decade. These advances motivate new missions that would test model predictions via multipoint in situ measurements and remote sensing. Simultaneously, further progress requires taking models to a new level to harness both the ever-increasing physical complexity and the rapidly changing supercomputing landscape, while adhering to the standards of open science. This conclusion applies to physics-based models across the entire field of solar and space physics.

1.2 SPACE WEATHER IN THE SERVICE OF HUMANITY

1.2.1 Space Weather Impacts Us All

The past decade marks a period when developed societies became truly space faring, as humanity depends increasingly on space-based communication, positioning, and navigation assets and applications, and as astronauts and commercial space travelers venture deeper into space. In addition, ground-based infrastructure has become more complex, relying on sensitive electronic components susceptible to electromagnetic disturbances driven by space plasmas and fields. As utilization of space continues to increase, the need to protect against the hazards of the space environment through advances in scientific knowledge will continue to grow.

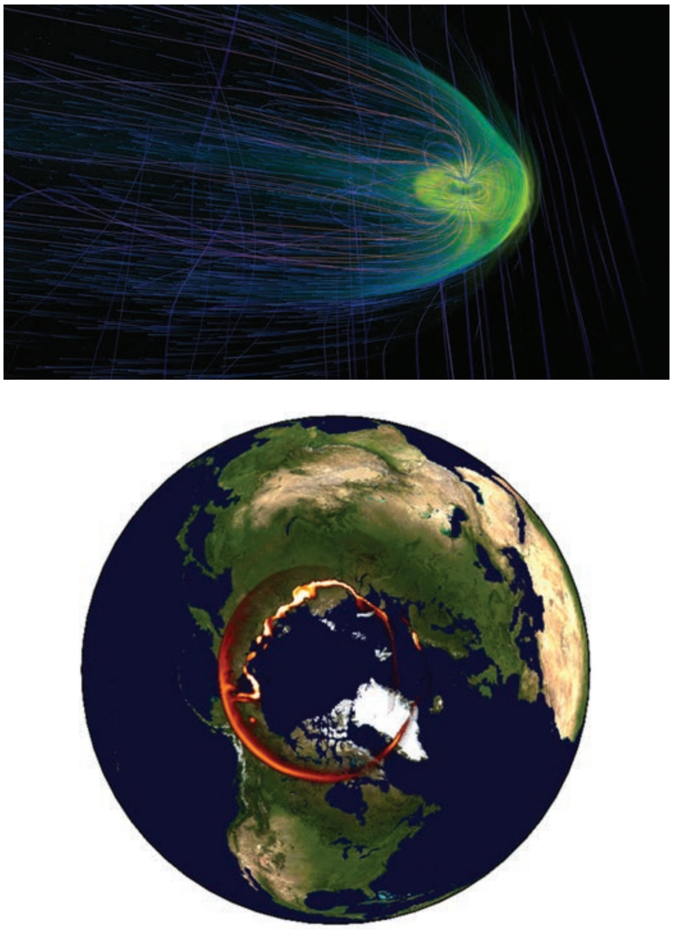

FIGURE 1-10 Model simulation of the magnetosphere from the Multiscale Atmosphere-Geospace Environment (MAGE) model (*Top*). Simulation of the February 3–4, 2022, geomagnetic storm, when a number of commercial satellites were lost as the atmosphere expanded. (*Bottom*). The aurora (northern lights, shown in orange) from a global geospace simulation, also from the MAGE model, shows the very high resolution that is possible from these advanced simulations.
SOURCES: (*Top*) NASA's Scientific Visualization Studio; (*Bottom*) NASA/Goddard Space Flight Center Scientific Visualization Studio; Blue Marble Next Generation data is courtesy of Reto Stockli (NASA/GSFC) and NASA's Earth Observatory. The MAGE simulation aurora image by V.G. Merkin and K.A. Sorathia.

Takeaways for Figures 1-9 and 1-10: (1) Physics-based models have progressed enormously in the past decade. (2) Models now make predictions that defy the ability to test them with existing data. (3) Model development has become as complex as space missions or ground-based facilities. (4) A new level of investment is necessary to exploit the opportunities to make further leaps forward in physics-based modeling across solar and space physics.

Space weather has become the applied branch of solar and space physics that addresses the adverse impacts of the Sun, its expanding atmosphere, and magnetic field on life and technologies at Earth, its atmosphere, space environment, and more generally everywhere in the solar system. Because the Sun is the primary origin of space weather, it behooves humanity to understand this star as it increasingly affects every aspect of technological society and lives. Figure 1-11 shows detection of active regions on the farside of the Sun using helioseismology. When combined with machine learning to predict the onset of flares from these active

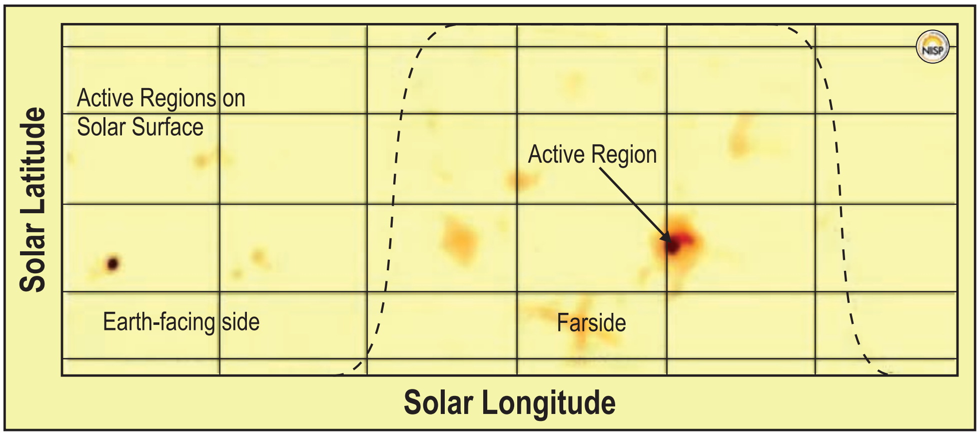

FIGURE 1-11 Helioseismology detection of an active region on the farside of the Sun. Solar flares result from localized active regions like these, and farside detection gives early warning of possible geospace disruptions at Earth over the coming days. SOURCES: Martinez-Pillet et al. (2020), https://baas.aas.org/pub/2020n3i110. CC BY 4.0.

Takeaways: (1) The Sun is the source of inclement space weather at Earth through a complex series of physical events and processes. (2) Inclement space weather is having an increasingly deleterious major financial and technological impact on space-based and ground-located assets, companies, industries, defense, and national interests. (3) Like Earth's weather, forecasting and nowcasting is critical to managing responses to space weather.

regions, these predictive capabilities, when fully developed, will provide predictions ranging from hours to days in advance, helping to protect humans, technologies, and infrastructure in space (satellites and high-altitude aircraft) and on the ground.

Space weather continually degrades space systems and causes errors in navigation, positioning, and communication systems. Severe space storms can debilitate entire power grids, generate hazardous radiation that harms aircraft and space-based crew, increase the risk of collision by nudging spacecraft and scrambling space debris orbits, and cause satellite subsystems to malfunction. The valuation of space weather risks is in excess of multiple billions of dollars (Figure 1-12) and has caught the attention of industrial, financial, defense, and commercial sectors and national and international legislative bodies.

While space weather observational needs are in part fulfilled by observations gathered from scientific missions, operational data are of great interest to the scientific community. Geostationary Operational Environmental Satellites (GOES) data have been used by the scientific community for 50 years. The next decade will take this duality to new levels. Space research increasingly needs multiplatform measurements to resolve space processes at all relevant temporal and spatial scales. The densely populated low Earth orbit offers especially excellent opportunities for both space weather research and service development through the deployment of simple instruments onboard commercial spacecraft. The impending solar maximum, predicted to be much more active than the previous one—with its increased space traffic management challenges, radiation damage, and communication malfunction potential—demands timely attention.

1.2.2 Space Weather Comes of Age

A little more than a decade ago, space weather was the orphaned child of space science, likely to be important in the future but unsure of where its home lay. Today, the specific congressional mandate and the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT 2020) codified the importance of space weather and assigned space weather roles to the National Oceanic and Atmospheric

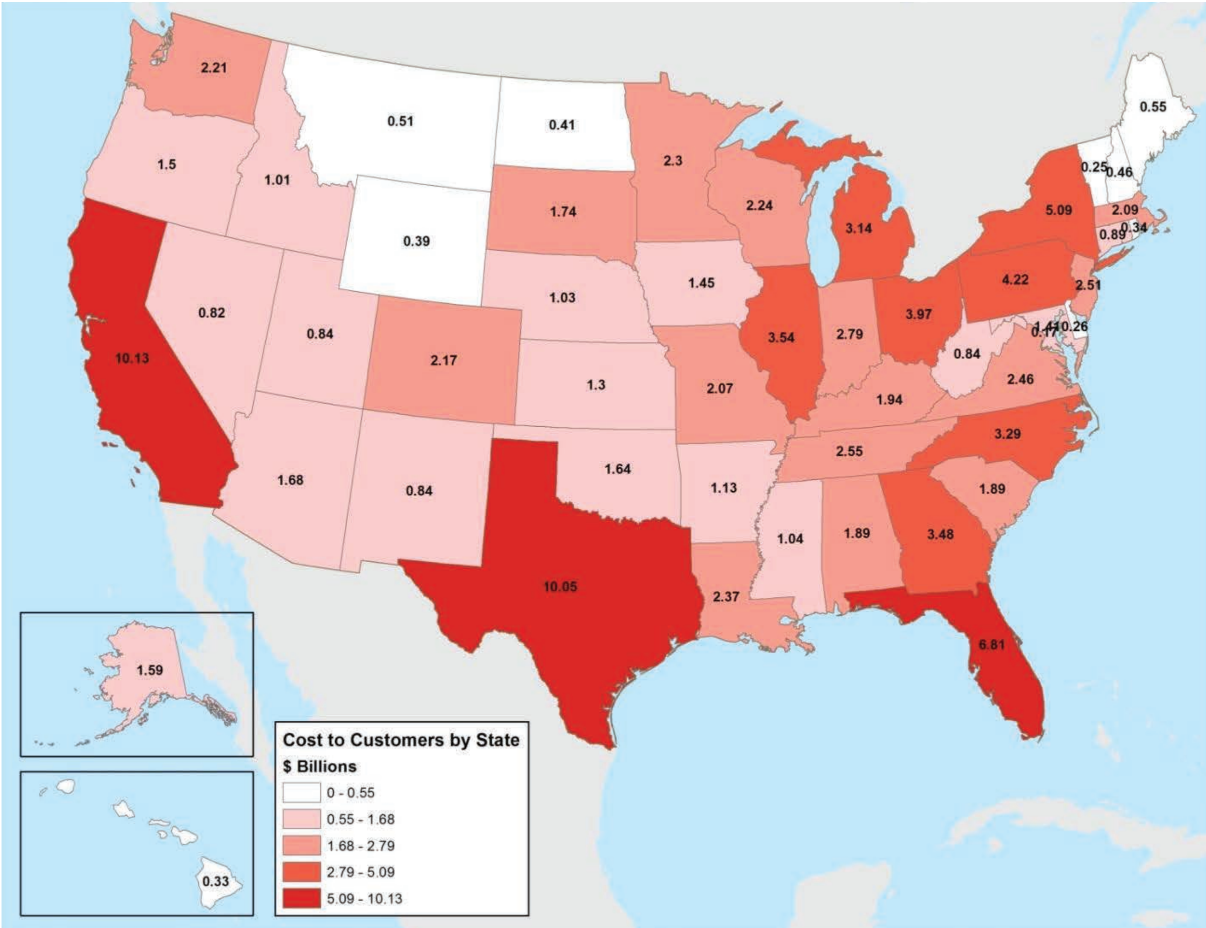

FIGURE 1-12 Cost estimates of a ~6-hour outage vary dramatically from state to state. State-level data are provided by the Energy Information Agency and the Department of Energy's Interruption Cost Estimate (ICE) calculator. The total cost may range from hundreds of millions of dollars to approximately $10 billion.
SOURCE: NOAA National Weather Service (2017).

Administration (NOAA), NASA, NSF, and other agencies. Initially space weather was the purview primarily of NOAA, augmenting its terrestrial weather capabilities and expertise, with NASA engagement beyond scientific research occurring on an ad hoc basis driven mainly by recommendations in the 2013 decadal survey, *Solar and Space Physics: A Science for a Technological Society* (NRC 2013; hereafter the "2013 decadal survey"). The 2013 decadal survey followed its statement of task, which focused on NASA and left a gray area between NASA and NOAA science and operations.

Space weather is a field that requires a solid scientific foundation, a national-level observing system, and a thorough understanding of the engineering solutions of the systems to be protected. To meet these demands, space weather solutions call for multidisciplinary, systems-level approaches. The National Space Weather Strategy and Action Plan (2019), the PROSWIFT Act, and the Space Weather Research-to-Operations and Operations-to-Research Framework (NSTC 2022) provide the requisite linking of science, national policy, and responsible parties. The legislation defined the respective roles and responsibilities of multiple agencies. For the first time, a framework for the modern era now exists for coordination of all sectors, from space weather researchers to forecasting operators and user groups, to address the protection of the nation's most precious assets.

1.2.3 The Growing Customer Base

At a September 2019 roundtable discussion hosted by the U.S. Chamber of Commerce and the SmallSat Alliance, Ajit Pai, former Chairman of the Federal Communications Commission, highlighted the importance of the space sector by stating, "Whether they know it or not, all companies will be space companies" (National Space Society 2019). Ajit Pai's prediction will almost certainly be true by the end of the coming decade. Figure 1-13 shows that the customer subscriber base to the NOAA Space Weather Prediction Center (SWPC) has grown exponentially since 2005 and today is approaching 80,000. Such a growth rate, if continued, predicts more than a million subscriptions by the end of the coming decade, making almost all companies "space companies." The enormous growth of satellites in low Earth orbit (pink line in Figure 1-13) is another strong indication of the ever-increasing demands on space weather resources.

1.2.4 Modeling the Space Weather System

Space weather prediction has taken giant leaps forward in the past decade. The upcoming decade promises extraordinary progress as the scientific and operational observation network grows and the numerical simulation, data assimilation and data science techniques, artificial intelligence methods, and the computational capacity continue to increase. The recently established NASA "proving ground" and NOAA "testbed" efforts support testing,

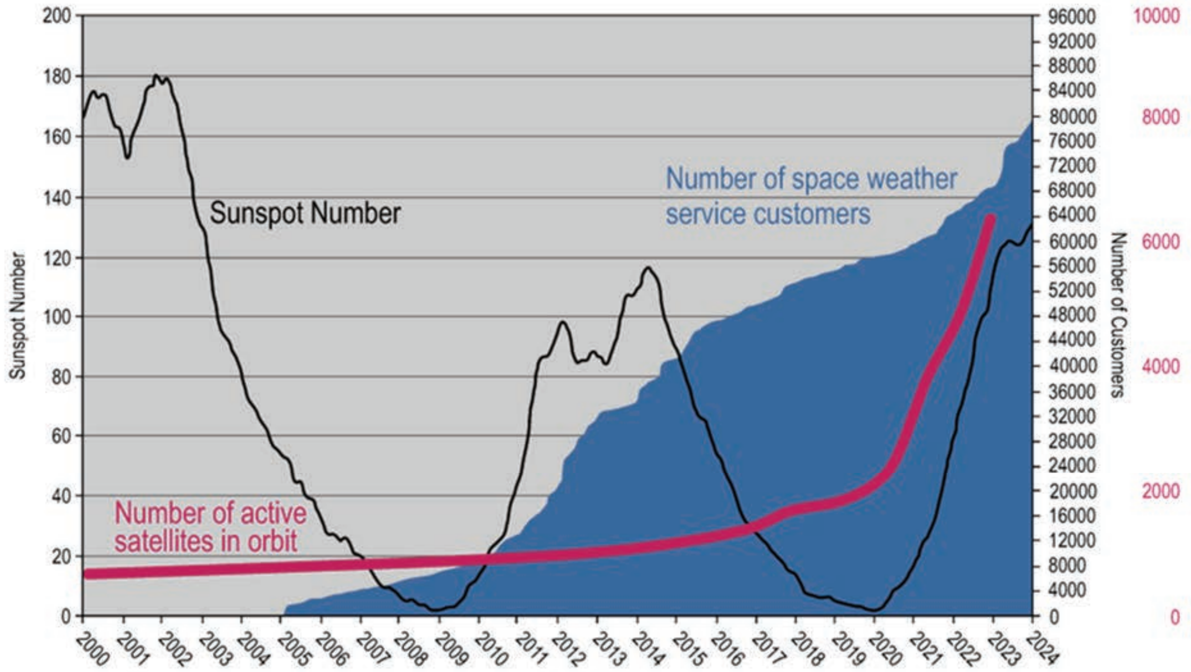

FIGURE 1-13 The NOAA Space Weather Prediction Center (SWPC) provides space weather-related alerts, warnings, watches, and forecasts to a wide range of subscribers, including but not limited to satellite operators, communications companies, the Federal Aviation Administration, and power system operators. There is a near exponential increase in the number of subscribers (the filled blue histogram) since 2005. The sunspot number is a proxy for solar activity and shows that the growth in subscribers is independent of solar activity.
SOURCES: Adapted from NWS/NOAA Space Weather Prediction Center (n.d.); Satellite data from J. McDowell (2024), https://planet4589.org. CC BY 4.0.

Takeaways: (1) There is a growing realization that space weather will impact all commercial sectors besides the obviously space-based technological, electrical grid, and spaceflight invested parties. (2) This is borne out by the exponentially growing number of subscribers to the NOAA SWPC subscription service. (3) A growing and broadening category of space weather services will be needed to meet the diverse needs of the commercial, industrial, federal, defense, research, and financial sectors.

validation, and transition from research to operations. Multiagency and international collaborations, as well as possible rideshares onboard the commercial fleet, offer new opportunities to enhance the observational network. These new opportunities in turn lay the groundwork for future scientific breakthroughs leading to increased lead time and accuracy of the forecasts and predictions. Figure 1-14 provides an example of space weather prediction capabilities and the promise of a future that ensures continued progress in providing the protection needed to mitigate the impacts of space weather storms.

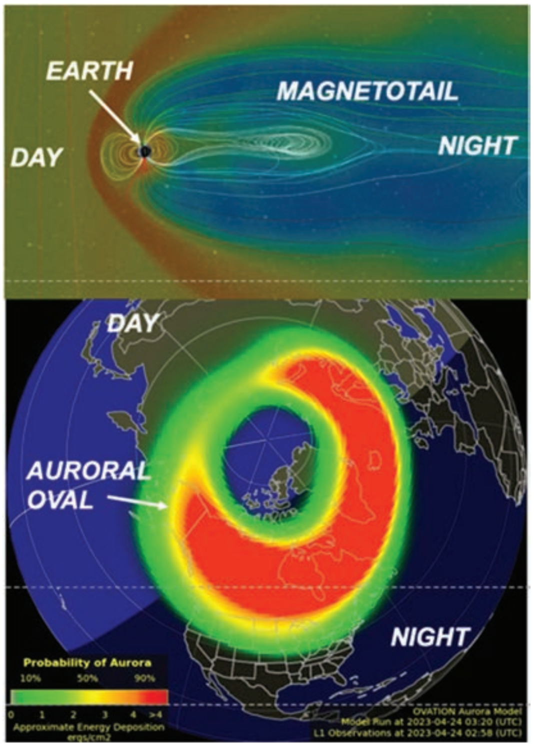

FIGURE 1-14 Numerical models are used to predict the state of the magnetosphere and ionosphere based on observations of the solar wind 1.5 million km away from Earth, giving a ~1-hour lead time before the onset of a geomagnetic storm. (*Top*) A snapshot from a numerical model simulating the dynamical evolution of the entire magnetosphere, including the magnetotail. (*Bottom*) A model-based auroral forecast, illustrating that during large storms the auroras, the associated electric currents, and space weather impacts often reach the continental United States. Both the Space Weather Modeling Framework Geospace and the Ovation Prime models are driven by solar wind observations and are operationally used at the NOAA Space Weather Prediction Center.
SOURCES: (*Top*) NASA's Scientific Visualization Studio, the Space Weather Research Center (SWRC), the Community-Coordinated Modeling Center (CCMC) and the Space Weather Modeling Framework (SWMF). (*Bottom*) NOAA/SWPC.

Models predict the impact: Solar eruptions expel large plasma clouds, coronal mass ejections, into interplanetary space. These clouds engulf Earth's space environment from about 15 hours to 2 days later, creating large geospace storms hazardous to both space- and ground-based systems and assets.

Takeaways: (1) The Sun has a major impact on the near space environment through the production of a dangerous damaging radiation environment. Coronal mass ejections can severely impact Earth's protective magnetic shield, the magnetosphere, and ionosphere. A variable solar wind and solar magnetic field similarly affects the magnetosphere. (2) Significant advances in numerical methods and computational power now allow, for the first time, scientists to model the space environment. NOAA Space Weather Prediction Center runs such models to predict geomagnetic activity in space, in the upper atmosphere, and on the ground. (3) The Space Weather Modeling Framework Geospace model describing the entire near-Earth space system down to 100 km altitude was transitioned from research to operational use in 2016. The WAM-IPE model describing both the neutral and ionized upper atmosphere up to about 600 km in altitude was transitioned to operations in 2021. Both are major steps forward for space weather research to operations capabilities.

1.3 MISSION AND VISION: TRANSITIONING TO THE NEXT DECADE

What lessons have been learned from the past decade and do they illuminate the path into the next decade? From the highlights above, several key general lessons are extracted.

1. Scientific breakthroughs often result from developing novel theories and models, instrumentation, and missions utilizing either or both in situ and/or remote imaging observations to explore new environments.
2. Transformative discoveries can come from exploring apparently familiar regions using multiple homogeneously or heterogeneously distributed spacecraft or vantage points to make coordinated multispatial, multitemporal, multiscale measurements. Improved instrumentation on these distributed spacecraft resolves relevant spatial and temporal scales, thus effectively using the "elements" to discover a "systems" perspective.
3. Theory, models, and observations that resolve the smallest (i.e., microscopes) or largest (i.e., telescopes) spatial and temporal scales answer long-standing fundamental questions, stimulate new theory and sophisticated simulations, emphasize that cross-scale coupling from micro- to meso- to macro-scales is critical to many unanswered problems, and elaborate the need for a systems-level understanding.
4. Space weather has come of age, and solar and space physicists are learning that the entire Earth, from subsurface to outer space, operates as a single highly complex and integrated coupled system. This system offers both protection and hazards to humanity's technological society.

These lessons, along with considerable community input, form the basis of the priority science in this report from the Committee for a Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033. The statement of task (see Appendix A) for this survey is broader than those of the previous two decadal surveys in solar and space physics. Notably, in addition to identifying priority science, the task included the following: assessing the space weather pipeline, from basic research to applications to operations, and identifying new and emerging frontiers where solar and space physics expertise enables significant advances. Guided by this statement of task and additional counsel contained in the study approach, recommendations made to the study sponsors—the Air Force Office of Scientific Research (AFOSR), NASA, NOAA, and NSF—constitute an ambitious but realistic approach for realizing identified scientific and space weather advances.

The four lessons above that form the cornerstone of the priority science portend the rich vein of discoveries for the next decade, not just in the heliosphere but in our very local region of the universe—what space physicists call "our local cosmos." A particularly promising research direction is the comparison of the Sun–Earth–heliosphere to other stellar systems. As humanity looks beyond the heliospheric boundaries to planets and astrospheres around distant stars, the ultimate question is whether life flourishes in these systems. Studying and understanding the only known habitable system in the universe, solar and space scientists are uniquely positioned to develop the theories and models that describe the stellar systems in the local cosmos, thereby defining the physical conditions that may enable life elsewhere in the galaxy. Contemporaneously, such knowledge is the cornerstone for protecting and safeguarding humanity and its technological society against the vicissitudes and dangers posed by inclement "space weather."

The aspirational vision for this decadal survey (Figure 1-15) focuses on discovering the mysteries of our local cosmos while also applying the knowledge gained to serve and safeguard humanity's home is space.

The solar and space physics vision and mission for the next decade and beyond translates into a broad set of themes that encompass the scientific and space weather goals for the next decade. The paramount strategy targets discoveries arising from new environments in novel ways, embracing the expansion of the field to cover the local cosmos and beyond. An overarching element underpinning these discoveries is understanding the processes from which this dynamic system is constructed. Under the umbrella of "Exploring Our Local Cosmos," the basic science themes for the next decade are as follows (see Figure 1-16):

- Sun–Earth–Space: Our Interconnected Home
- A Laboratory in Space: Building Blocks of Understanding
- New Environments: Exploring Our Cosmic Neighborhood and Beyond

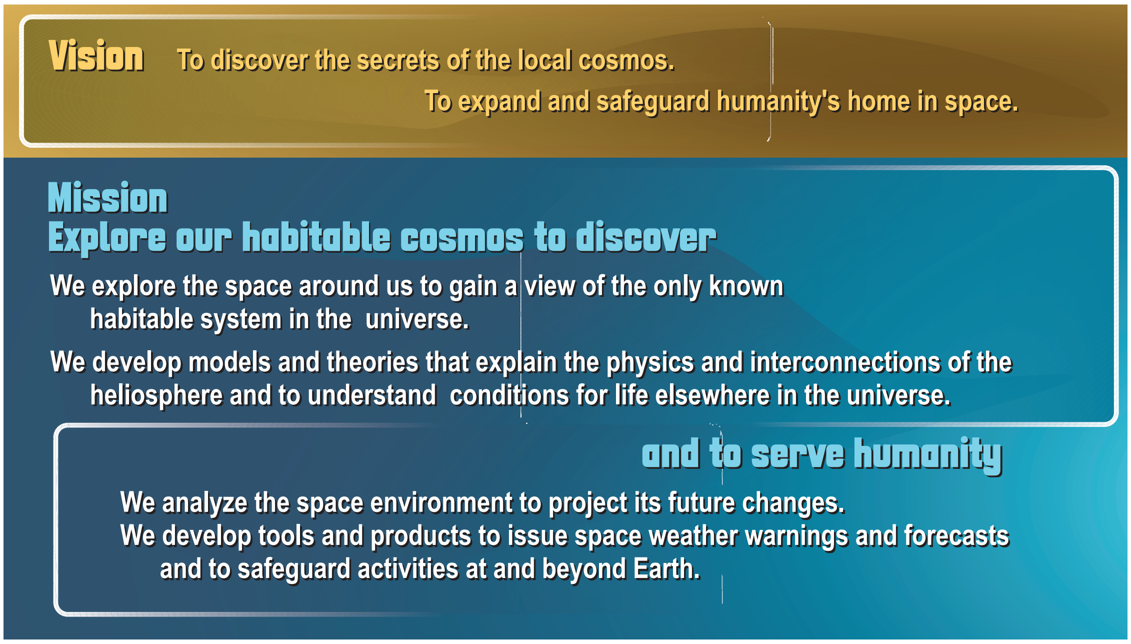

FIGURE 1-15 Solar and space physics vision and mission for the next decade and beyond.
SOURCE: Composed by AJ Galaviz III, Southwest Research Institute.

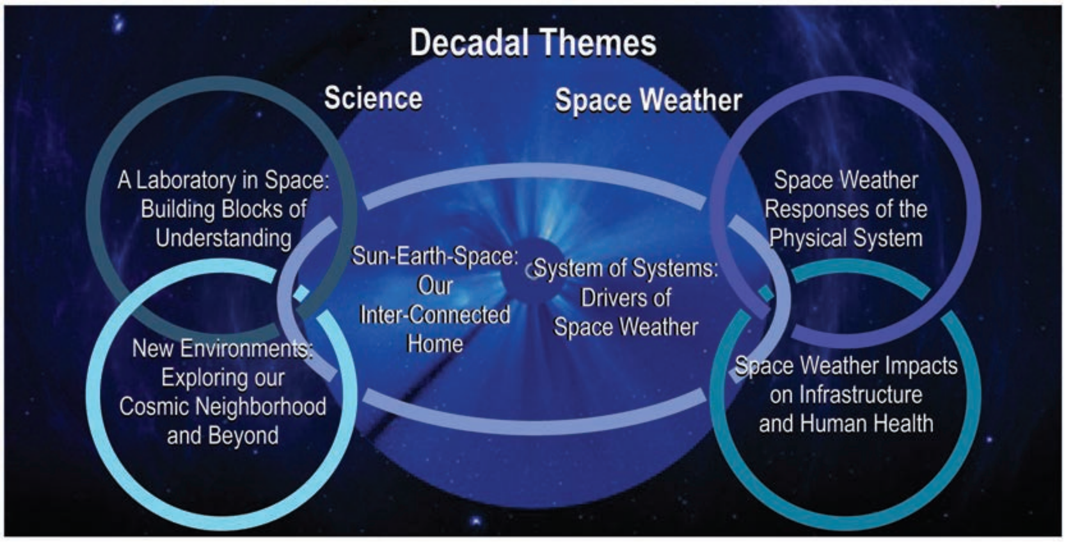

FIGURE 1-16 Schematic illustrating the interlinked science and space weather themes, effectively forming "two sides of the same coin."
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Center image from NASA, U.S. Naval Research Laboratory.

These science themes are integrally linked to a set of themes that shape space weather research for the next decade. For space weather, it is important to address individual impacts on particular physical systems as well as on technological systems and humans in space, in the air, and on the ground. Under the umbrella of service to humanity, the three space weather themes for the next decade are as follows (see Figure 1-16):

- System-of-Systems Drivers of Space Weather
- Space Weather Responses of the Physical System
- Space Weather Impacts on the Infrastructure and Human Health

These six themes provide a thematic roadmap for the science and space weather goals of the next decade and beyond and are discussed in detail in Chapters 2 and 3. The flow-down from the science and space weather themes is shown in Figure 1-17. Because science and space weather goals are not accomplished without a vibrant and engaged solar and space physics community, this evolving workforce and the challenges for the next decade are discussed in Chapter 4. In Chapter 5, the science, space weather, and state of the profession come together in a comprehensive, balanced, and integrated research strategy. In Chapter 6, the integrated research strategy is summarized and the budget implications for this strategy are considered.

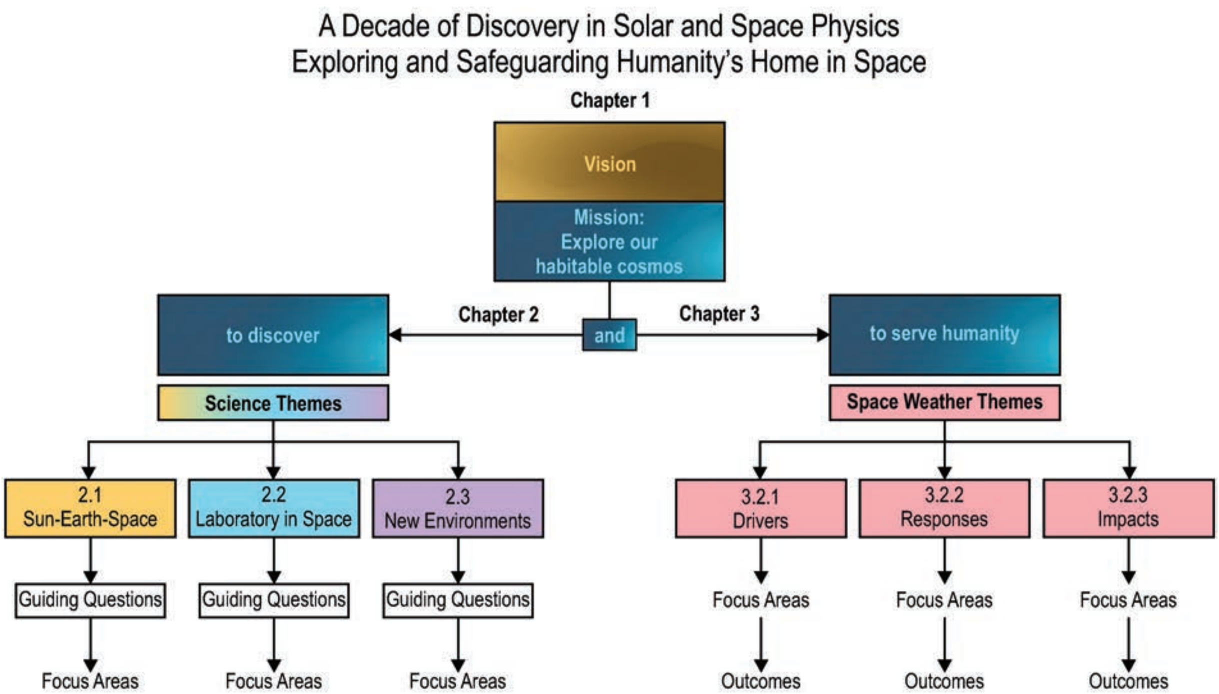

FIGURE 1-17 Flowchart for Chapters 2 and 3 showing how the two-part mission statement is divided between science in Chapter 2 and space weather in Chapter 3. Each of the three science themes has guiding questions and focus areas associated with it. Each of the three space weather themes has focus areas and outcomes associated with it.
SOURCE: Composed by AJ Galaviz III, Southwest Research Institute.

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2

New and Emerging Frontiers in Science

The achievements of the past decade that are sampled in Chapter 1 informed the first part of the solar and space physics "mission" (see Figure 1-15) to explore our habitable cosmos. They also informed the development of the three themes (see Figure 2-1) that the committee used to prioritize science for the next decade. The three science themes—interconnectedness, building blocks, and new environments—capture and combine common threads within the field of solar and space physics. These themes are deliberately broad, mostly region or subdiscipline agnostic, and encompass a wide range of solar and space physics science in a balanced fashion. The science themes for the next decade in Figure 2-1 emerged from the community white papers (henceforth called community input papers) and panel reports (included as appendixes) that identified many high-priority science goals while broadly spanning the entirety of the decadal survey's statement of task.

Each broad science theme poses guiding questions (as listed in Figure 2-1), which serve to steer the research of the next decade. The individual guiding questions are not as broad as their associated themes; substantive progress in addressing these questions is possible in the next decade. This progress critically hinges on timely and complete implementation of the comprehensive and balanced research strategy described in detail in Chapter 5.

The three sections below expand on science themes and guiding questions. Under each guiding question, there are several focus areas that tie directly to specific, notional projects in the research strategy described in Chapter 5, where specific recommendations directed at the research strategy can be found. As the name implies, the focus areas are deliberately designed to target a particular aspect of a guiding question, and therefore are a prioritization of the science of the next decade. However, complete answers to every guiding question are not possible in the next decade. Furthermore, scientific discovery and progress rarely takes a direct path from a focus area through a guiding question to a theme. The discoveries of a third Van Allen Belt, the PSP magnetic switchbacks, and the understanding of the origin of the IBEX Ribbon (Funsten et al. 2009) are recent examples of the unexpected trajectories of science research, where discoveries led to follow-on research and new questions. Emerging questions lead to new missions or ground-based projects with unheralded objectives. The 2013 decadal survey contains an excellent example of such evolution, as many of the science objectives of the Interstellar Mapping and Acceleration Probe (IMAP) mission were not even conceived prior to the discovery of the IBEX Ribbon. Thus, to allow for scientific discoveries in the next decade, there is room within the guiding questions for research projects, theory and modeling efforts, targeted space missions, and ground-based projects that tackle specific aspects of each question.

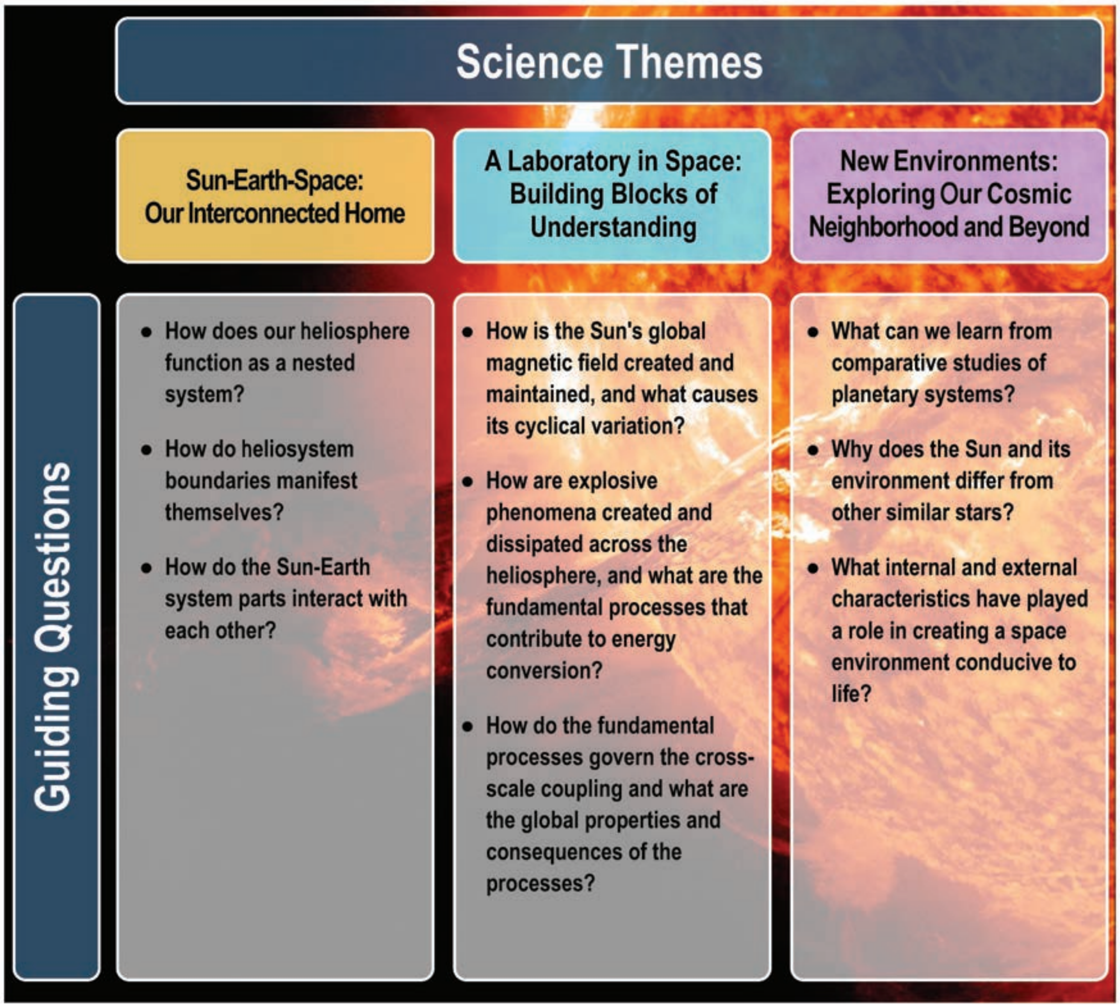


FIGURE 2-1 Building on the successes of the previous decade and considerable community input, each science theme in this chapter has guiding questions associated with it that serve to steer the research of the next decade. Substantive progress is made on these guiding questions through focus areas that prioritize the science. The guiding questions and focus areas are described in more detail in the subsequent three sections of this chapter.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Background image from NASA/Goddard Space Flight Center.

2.1 THEME 1—SUN–EARTH–SPACE: OUR INTERCONNECTED HOME

The Sun constantly expels a wind of electrically charged particles (plasma) into space, carving out a bubble called the heliosphere. The local cosmos, dominated by the energy released by the Sun, provides an opportunity to study plasma and neutral interactions ranging from those deep in the Sun's interior, to those in the solar atmosphere, the solar wind, magnetospheres and atmospheres of planets and moons, and the farthest reaches of the solar system where the solar wind slams into the interstellar medium.

All these natural systems, called "heliosystems" in this report, are vast reservoirs of plasmas, energetic particles, neutral gases, and electromagnetic fields that exhibit complex interactions within and amongst themselves. Since the beginning of the space age, the solar and space physics community has made enormous strides in understanding these heliosystems. The community has matured; in addition to new discoveries, much progress is being made in uncovering the global structure and fundamental processes of these systems.

The discoveries in the past decade show that there are still surprises in these heliosystems; however, these discoveries have led to perhaps the most significant outcome of all: *the heliosphere as a whole, and its various parts, behave as a complex system of systems*. To understand the behavior of this home in space, it is imperative to understand how each of these systems functions and how they interact with each other. Small scales (where kinetic processes are important) influence large scales (encompassing significant parts of a system), and charged particles and neutrals interact with one another. Fields and waves modify the characteristics of charged particles, which in turn shape the fields and waves. Together, these interactions result in emergent system behaviors—phenomena that are only present as a result of the interaction of all the parts. These phenomena include some of the most visually spectacular phenomena known to humankind. Two examples are coronal mass ejections (CMEs) from the Sun and aurora created in planetary atmospheres.

Achieving a systems-level understanding of phenomena like CMEs and the aurora requires new, strategic research approaches whereby space missions, ground-based facilities, theory, modeling, and data analytics are used in an orchestrated program that addresses the interactions among and between its subsystems. These interactions often happen on scales that are intermediate between the small and large scales and are challenging to address from either the kinetic or from the global system point of view.

The National Aeronautics and Space Administration (NASA) Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission was a trailblazer in such systems science, with its five spacecraft and a dense network of ground-based, high-latitude, all-sky imagers. This Medium-Class Explorer (MIDEX) mission unequivocally demonstrated the power of coordinated ground-based and multispacecraft observations. Such distributed observing systems require collaboration between research teams leading the space mission and ground observatory development, and coordination and cooperation between the respective funding agencies (most notably NASA and the National Science Foundation [NSF]). Solar and space physics is now at a pivotal point, where the next major advances depend critically on effective mechanisms to obtain the necessary spatial coverage by combining space missions with simultaneous, coordinated ground-based observations and global modeling. The next decade thus heralds the arrival of a new, transdisciplinary branch of solar and space physics—heliosystems science.

The science theme Sun–Earth–Space: Our Interconnected Home centers on this systems aspect and contains three guiding questions that each have several research focus areas where significant progress is planned for the next decade (see Figure 2-2). The guiding questions with their tangible focus areas are discussed in detail below. The questions flow from understanding the entire system as a whole (“nested system”), to uncovering processes at the boundaries, to examining the detailed interactions between two of the system components.

2.1.1 Guiding Question: How Does Our Heliosphere Function as a Nested System?

The primary energy source of the heliospheric system is the Sun. The Sun’s magnetic dynamo produces magnetic fields that evolve in a complex and cyclic manner over a wide range of spatial and temporal scales. These magnetic fields structure the solar atmosphere and are drawn out into the solar wind. Upon leaving the Sun, the plasmas and fields encounter planets, comets, dust, and last, interplanetary space, creating a complex set of interactions and new dynamical systems. Solar system bodies can have internal magnetic fields, atmospheres, and their own energy sources. Each dynamical system is driven by a unique combination of solar energy input and internal mass, magnetic field, and dynamic processes. The nonlinearity of the systems, the complexity of the interactions, and the sensitivity of the dynamics to the small changes in the previous state make understanding and predicting this fascinating system of systems challenging.

Energy and Momentum Flow Across and Within the Heliosystem Parts

This focus area has three related topics: Solar Magnetic Field Through the Heliosphere, Energy Transfer Across Boundaries, and Energy Exchange Between Plasmas and Neutrals.

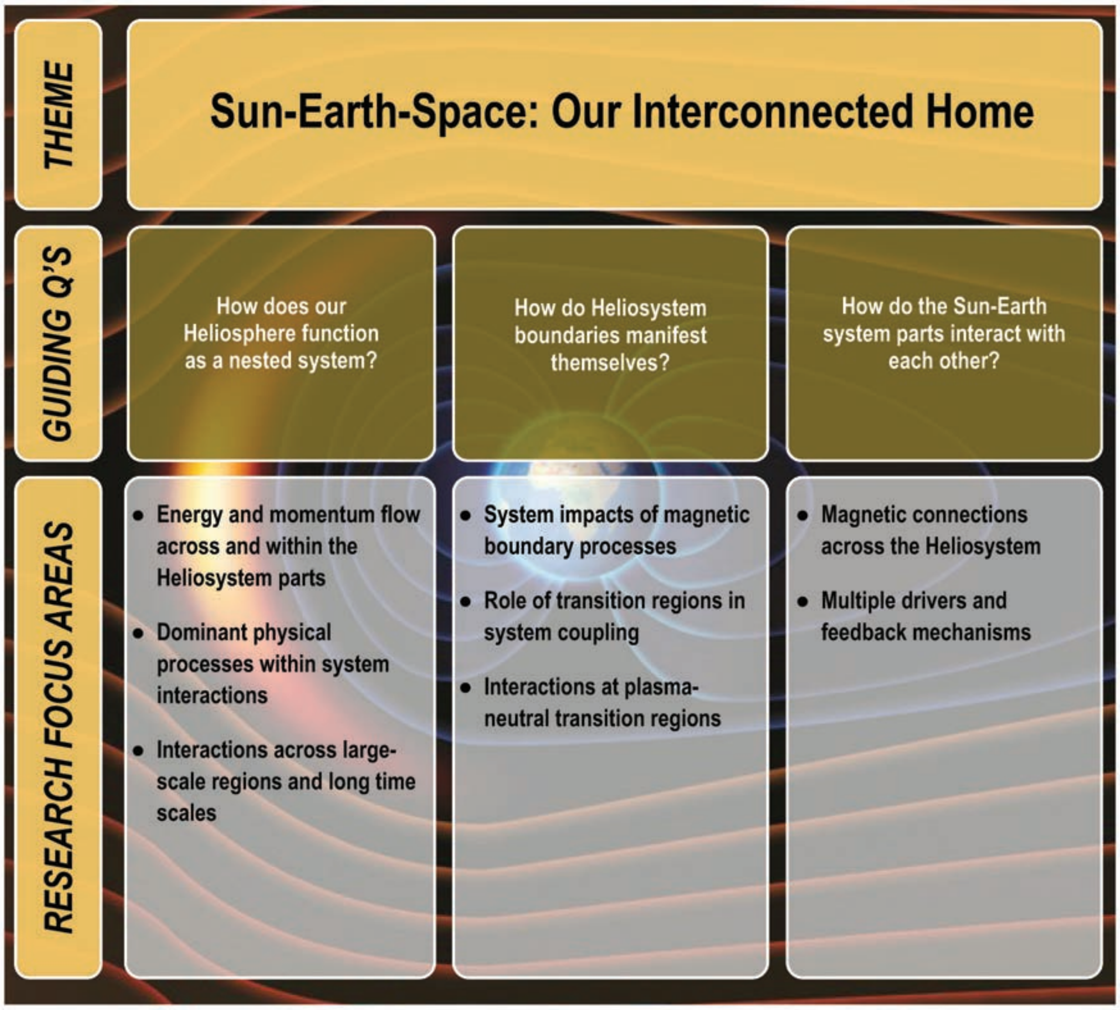


FIGURE 2-2 Guiding questions and research focus areas within Theme 1—Sun–Earth–Space: Our Interconnected Home.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Background image from Naeblys/Shutterstock.com.

Solar Magnetic Field Through the Heliosphere

A vast amount of magnetic energy is released into interplanetary space through explosive events, such as solar flares and CMEs. Multipoint spacecraft measurements resolved how CMEs are released and how they evolve with distance from the Sun. However, the in situ observations and remote observations from a single perspective during the propagation of any of these structures through the heliosphere leave major questions unresolved about the solar sources and generation processes of CMEs as well as their expansion into the heliosphere.

Major challenges for the next decade are to understand the generation of magnetic fields inside the Sun, their emergence into the solar atmosphere, and how this magnetic field is carried by the supersonic solar wind to the outer heliosphere where it couples to the local interstellar medium. Further understanding of the origin of the Sun's magnetic field and the fundamental role it plays in energy release requires measurements of the solar magnetic field as a function of latitude and longitude from the interior, through the surface (photosphere), up into the atmosphere (chromosphere and corona), and into the solar wind. Multiple techniques and multiple vantage points, particularly out of the ecliptic plane, coupled with extensive modeling, are therefore required. In the following, the broader (italics) science questions are followed by selected examples where recent observations have indicated future research needs, while many others would naturally also fall under the titles

Energy Transfer Across Boundaries

Solar wind structures such as CMEs and fast solar wind streams impact the magnetospheres of Earth, other planets, and solar system bodies. The energy that these structures carry powers explosive magnetic reconfiguration processes as well as particle energization processes—such as magnetic reconnection—enabling energy, momentum, and plasma transport from the solar wind into the planetary space environments (magnetospheres). In the past decade, the MMS mission unraveled the micro-scale processes driving magnetic reconnection at Earth's magnetic boundary and in the magnetotail. Now that the microphysics has been elucidated, major open questions are centered on the relative importance of solar wind and atmospheric driving (e.g., energy transferred from the lower atmosphere into the upper atmosphere and ionosphere) on meso- and global-scales, and whether the driver dominance varies for different processes and dynamic conditions.

In space plasmas, the flows and fields are impacted by microscale processes (e.g., turbulence or magnetic reconnection), driven by large-scale processes (e.g., solar wind coupling in the case of the magnetosphere), but they also produce structures (either spontaneously or in response to external processes) at intermediate or mesoscales, and these structures can have major impacts on large-scale dynamics (e.g., energy transfer across the magnetopause or energy release in a substorm).

Resolving these energy transfer processes and the dynamics leading to magnetospheric reconfiguration events requires spacecraft constellations that can resolve the mesoscales, combined with remote sensing observations of the broad region covering several mesoscale structures. Moreover, because the ability to cover the vast region of space is limited, these observations need to be complemented by comprehensive numerical modeling (see Figure 2-3).

Energy Exchange Between Plasmas and Neutrals

Explosive energy release events in the magnetosphere lead to a series of coupling processes connecting Earth's high-altitude magnetosphere to the upper layers of the atmosphere, comprising the ionosphere, thermosphere, and

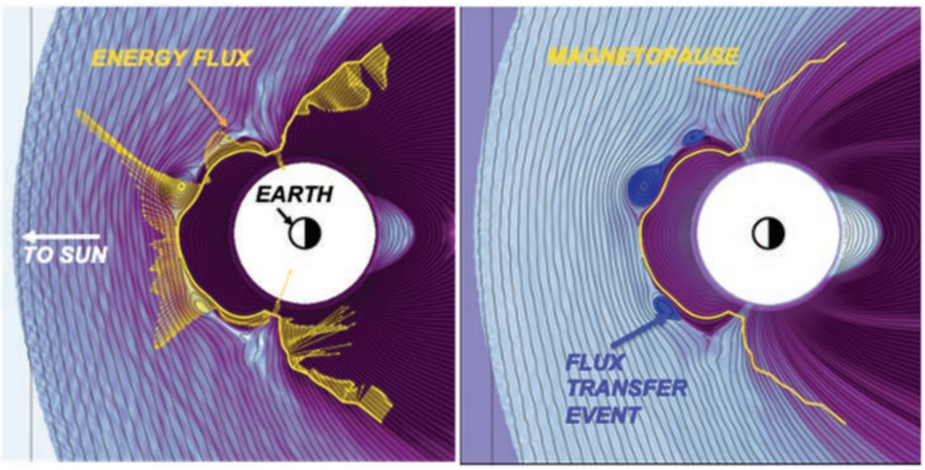


FIGURE 2-3 As the solar wind flows past Earth, the magnetospheric boundary is continuously exchanging shocked solar wind and magnetospheric mass and energy. The yellow arrows show the direction of the energy flow from a simulation using the Vlasiator code. The energy transport is characterized by mesoscale transient events, called flux transfer events, which deform the boundary and create new entry and exit pathways, creating transport across the entire boundary. Determining mass and energy flow of flux transfer events from single-point space measurements is challenging.
SOURCE: Modified from Ala-Lahti et al. (2022), https://doi.org/10.1029/2022GL100079. CC BY 4.0.

mesosphere. In addition, the upper atmosphere is "forced" from above by solar and other influences and from below by various processes and activities occurring in the lower atmosphere. The upper atmospheric system is driven from above by absorption of solar radiation, plasma transport between the ionosphere and plasmasphere, and gravitational escape of light neutrals (Figure 2-4). The state of the upper atmosphere also is strongly influenced from below—by neutral particle composition, winds, and temperature variations originating from the lower atmosphere (stratosphere and troposphere). Furthermore, there is transport of mass, momentum, and energy across internal transition regions within the upper atmospheric system itself, as it changes from a well-mixed, mostly neutral gas to a partially ionized, nearly collisionless region at higher altitude. However, current observational methods do not distinguish the relative roles of driving from above and below, nor do they follow the dynamics in sufficient detail to pinpoint the sequences of events under dynamic conditions.

The planned multiplane, multialtitude constellation ionospheric missions, Geospace Dynamics Constellation (GDC) and Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC), will provide critical information on the electromagnetic system inputs at midlatitudes and high latitudes, and on the ways the upper atmospheric system processes and redistributes the inflowing energy.

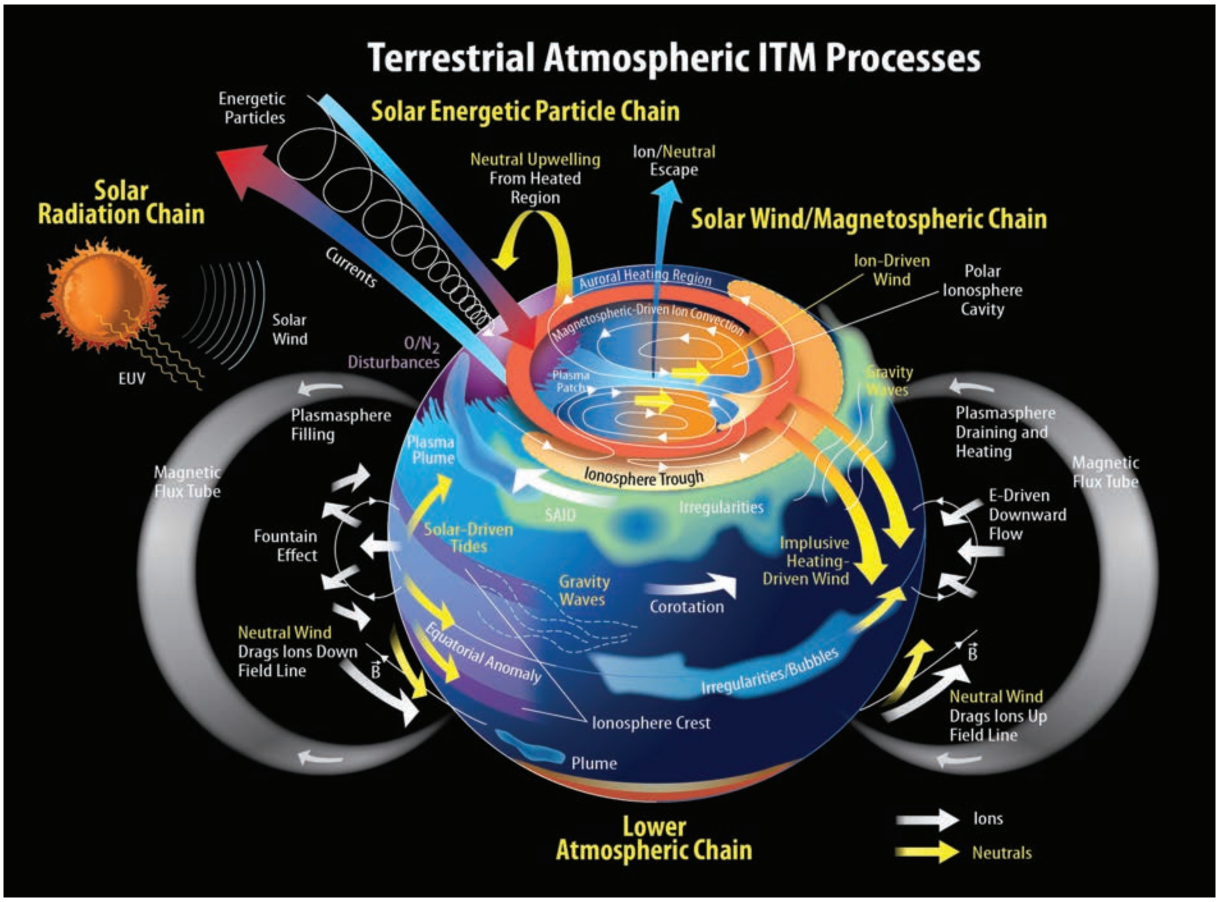


FIGURE 2-4 The complexity of the combined effects of plasma physical processes associated with solar wind impacting Earth and the solar radiation effects, tides, gravity waves, and neutral winds in the neutral atmosphere. The interlinked systems generate a complex set of time-varying electric currents connecting the ionosphere to the high-altitude magnetosphere, upward and downward motion of electrons and ions, as well as upflow of atmospheric neutrals. Polar region ionospheric ions and electrons are set into a circulating motion, interacting with and impacting the neutral atmosphere. While each of these systems may be studied in isolation, the full dynamic evolution is only understood by considering all elements of the coupled systems. SOURCE: NASA's Scientific Visualization Studio.

Energy exchange between plasmas and neutrals occurs in many contexts. On the Sun, ambipolar diffusion is implicated in the ubiquitous presence of plasma jets called "spicules" in the solar chromosphere. Their role in the mass and energy budget of the corona and solar wind remains an active area of intense interest.

Dominant Physical Processes Within System Interactions

The Sun, the solar wind, and the planetary space environments are composed of distinct plasmas that each have their own characteristic composition and energy distribution, and these plasmas have their own dynamical evolution that is governed by different physical and chemical processes operating at various temporal and spatial scales. Nonlinear processes comprise instabilities and feedbacks and depend on both the available energy and the dynamic states of the interacting systems. Recent advances in large-scale numerical simulations have for the first time allowed comprehensive modeling of several parts of the system at the same time. However, the systems and their interactions are so complex and occur over such large distances that current observations cannot quantitatively determine the interaction drivers and responses in any single event.

This focus area has two related topics: Reconnection Driving Explosive Events in the Solar Atmosphere and Plasma Composition Effects for System Interactions.

Reconnection Driving Explosive Events in the Solar Atmosphere

One longstanding problem in solar physics is explaining the sudden, localized conversion of magnetic energy to radiation, energized plasma, and energetic electrons and ions. Another related problem is explaining the transport of these converted products in solar flares and their impact on the solar atmosphere and their escape into the interplanetary medium. In the past decade, significant advances in understanding were enabled by pathfinding observations at multiple wavelengths, including radio observations of the coronal magnetic fields and the evolving particle distributions by the Expanded Owens Valley Solar Array (EOVSA), hard X-ray and gamma-ray observations from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), and ultraviolet/extreme ultraviolet (UV/EUV) band recordings of the dynamics by NASA's Interface Region Imaging Spectrograph (IRIS) and Solar Dynamics Observatory (SDO).

Further progress requires more comprehensive radio imaging and polarimetric observations across a broad frequency range. These observations are needed to quantitatively measure magnetic fields, properties of the thermal plasma, and the production and transport of nonthermal electrons throughout the solar atmosphere. The observations need to be coupled with imaging spectroscopic measurements from UV to gamma-ray energies as well as in situ measurements of energetic electrons and ions from multiple vantage points to effectively observe the corona as a system across multiple scales.

Plasma Composition Effects for System Interactions

The details of plasma composition provide fundamental clues about the nature and origin of a wide variety of phenomena, such as the first ionization potential (FIP) effect that impacts solar coronal abundances. In the near-Earth region, the plasma is a composite formed of solar energetic particles, the solar wind, and the planet's atmosphere. Missions in previous decades have established that plasma sources include sputtering from the surface (mostly atmosphere-less planets); ionospheric outflow through a variety of processes; and the solar wind, mainly through magnetic reconnection. Any given dynamic state is a combination of the source and a variety of transport and energization processes active in the magnetotail (reconnection-driven convection and acceleration, rotational driven transport, acceleration by field-aligned potential drops, and other nonadiabatic processes) as well as loss processes such as plasmoids, charge exchange, and particle precipitation. At any given time, the relative importance of solar and atmospheric sources in different parts of the magnetosphere depends on solar UV flux and solar wind drivers as well as the dynamic state of the ionosphere–thermosphere–mesosphere (ITM) system. Mass-resolved ion composition measurements are needed, preferably in the solar wind source region, in and above the ionosphere source region, and in the magnetosphere where the source populations mix. These measurements provide high-quality observational constraints on the system's boundary conditions.

Interactions Across Large-Scale Regions and Long Timescales

The unexplored frontiers of the outer heliosphere and local interstellar medium await new discoveries. The interaction of the solar wind with the interstellar medium creates a complex and dynamic system comprising a termination shock and the heliospheric boundary (heliopause). Near Earth, the magnetosphere and ionosphere are coupled by complex electrodynamic processes occurring at multiple temporal and spatial scales. The upper atmosphere system responds to persistent changes in the lower atmosphere, of both natural and anthropogenic origin, that vary the state of this system on timescales comparable to the sunspot cycle.

This focus area has two related topics: Particle Acceleration and Transport Near Plasma Boundaries, and Electromagnetic Coupling.

Particle Acceleration and Transport Near Plasma Boundaries

The past decade brought discoveries that generated ongoing debates on particle acceleration at plasma boundaries; for example, the boundaries of the heliosphere. As the Voyagers continue their epic journey in the very local interstellar medium, their measurements of magnetic fields, plasma, and energetic particles have indirectly elucidated the critical role that interstellar pickup ions play in shaping both the physics and structure of the heliosphere. For example, Voyager 1 revealed indirectly that the primary dissipation mechanism governing the heliospheric termination shock is pickup ions and not thermal solar wind ions, subsequently confirmed by direct pickup observations made at distant interplanetary shocks by New Horizons. The New Horizons spacecraft, currently on its way outward beyond the planetary system, measures pickup ions and thermal solar wind ions in the outer heliosphere, providing the most complete measurements of their properties so far. Anomalous cosmic rays come from acceleration of pickup ions. The overall shape of the heliosphere, and in particular the heliotail, is still under debate, even as the Voyagers measured the termination shock and heliopause, and the Interstellar Boundary Explorer (IBEX) remote sensing observations revealed how the boundary responds to the pressures of solar wind from the inside and the very local interstellar medium (VLISM) from the outside. Last, the boundary region accelerates and deflects cosmic rays in ways that are still not understood but have significance to the cosmic ray flux at Earth orbit. Such questions are only answered by in situ measurements of the magnetic fields and particle distributions covering the relevant energy scales. In the next decade, the IMAP mission will provide more detailed remote sensing observations of the outer heliosphere which, combined with modeling, will unravel the boundary structure.

Electromagnetic Coupling

The existence of a tight physical coupling between the magnetosphere and ionosphere has been deduced from observing the aurora and magnetic perturbations in the ionosphere and from multipoint measurements in the magnetosphere. These observations have revolutionized the understanding of the spatial structure and dynamics of field-aligned currents connecting the magnetosphere to the ionosphere and painted a more detailed picture of the dynamics of ionospheric plasma density, flows, and currents. Yet, there are major gaps in the understanding of the magnetosphere–ionosphere coupling processes. The multiprobe GDC mission will provide critical measurements quantifying the energy flow from the magnetosphere to the ionosphere across multiple scales, thus resolving the energy partitioning between particles and fields as well as distribution across different spatial and temporal scales.

In the next decade, combining new observations with system-level models has the potential for a quantum leap in how magnetosphere–ionosphere coupling is understood. However, this advancement requires several transformative steps in how the coupled system is treated: The thermospheric neutral winds need to be coupled to the ionospheric electrodynamic models for the conductivity, electric fields, and currents (see Figure 2-5). The current two-dimensional ionospheric electrodynamics models need to be replaced by three-dimensional ionosphere–thermosphere models that extend over all latitudes. Last, these new models must include inductive magnetosphere–ionosphere coupling that accounts for time-varying electromagnetic fields and resolves spatial and temporal scales that have remained elusive in current system-level models.

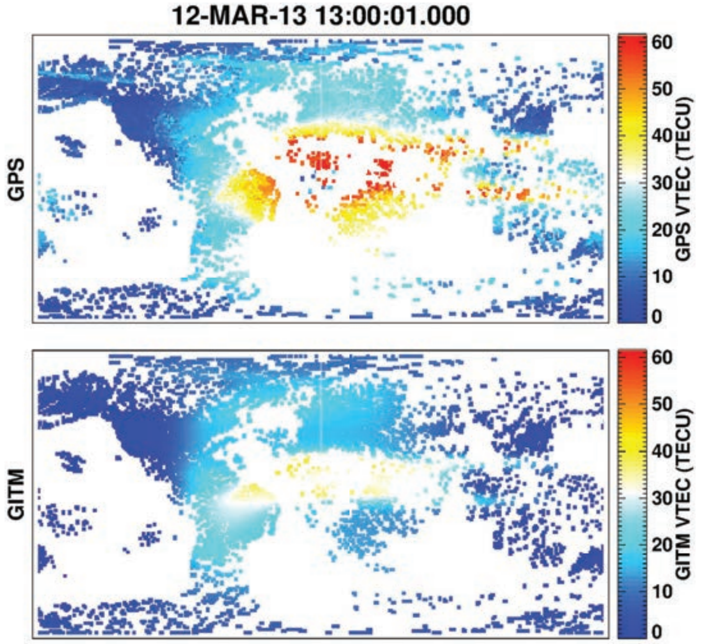


FIGURE 2-5 An illustration of the ability of ionosphere–thermosphere models to describe the coupled processes between the neutral atmosphere and the ionosphere (see Figure 2-4). One of the key parameters describing the system state is the total electron content (TEC) across the ionospheric altitudes. This parameter is derived from distortions observed in the Global Positioning System (GPS) satellite signals, provided a sufficiently dense network of both transmitting spacecraft and receiving ground stations are available. The figure shows a comparison of the GPS-derived TEC measurement (*Top*) compared with the Global Ionosphere–Thermosphere (GITM) model results (*Bottom*), showing that the model captures the large-scale structures but misses some of the highest intensities. Although not shown here, this underestimation leads to corresponding overestimation of the neutral thermospheric winds, highlighting the strong coupling between the neutral atmosphere and the ionosphere dominated by electromagnetic forces.
SOURCE: Brandt and Ridley (2022), https://doi.org/10.1029/2021SW002922. CC BY 4.0.

2.1.2 Guiding Question: How Do Heliosystem Boundaries Manifest Themselves?

In most space environments, magnetic fields enclose plasmas, separating them into distinct regions and restricting their mixing across the plasma boundaries defined by the field topology. Shocks, another class of narrow layers that separate two different plasma states, are abundant in the Sun and in the interplanetary medium. In addition, bow shocks form as a consequence of the interaction of the supersonic solar wind with the planetary magnetic fields, ionospheres, and atmospheres.

However, not all boundaries in space plasmas are sharp transitions across a (rotational or tangential) discontinuity or a shock. For example, layers of the solar atmosphere are identified by their temperature, density, ionization state, and the relative roles of gas and magnetic pressure, each changing continuously with altitude. The transition layer between the chromosphere and corona is mainly characterized by the sharp increase in temperature and simultaneous decrease in the plasma density. In the coming decade, these layers, and their interactions and couplings, will be probed by the Japan-led Extreme Ultraviolet High-Throughput Spectroscopic Telescope Epsilon Mission (EUVST) and NASA's Multi-slit Solar Explorer (MUSE). Analogously, in Earth's thermosphere, the atmosphere transitions from almost entirely neutral composition dominated by turbulent mixing to increasingly ionized with changing temperature and composition and diminished role of collisions between particles. These layers will be probed using a variety of techniques.

In the magnetosphere, the transition from the quasi-dipolar magnetic configuration in the inner magnetosphere to the cometary-like magnetotail occurs over a relatively short radial distance but marks a dramatic change in plasma and field conditions. This transition region is critically important, as it is the source of auroral precipitation and is home to many plasma transport and energization processes that contribute to the explosive energy release in substorms and the transport of energy and magnetic flux during geomagnetic storms. Many of these processes occur at mesoscales that are between the global scales of the system and microscales where kinetic physics becomes important. Probing these intermediate scales is equally challenging for simulations and observations. The former require high-resolution, complex models, while the latter require high-resolution, multipoint measurements combined with remote sensing.

System Impacts of Magnetic Boundary Processes

This focus area has three related topics: Boundaries as Source Regions, Local Processes Driving Large-Scale Energy Transfer, and Mesoscale Dynamics Within the Magnetosphere's Transition Regions.

Boundaries as Source Regions

Magnetic boundaries separate the closed magnetic flux of the active corona from the open flux in the solar wind. The magnetic interchange reconnection process is prevalent across this boundary as it moves through the heliosphere. Magnetic reconnection between an open and closed magnetic field is described as "interchange" reconnection. This results in the opening of formerly closed field lines and the closing of formerly open field lines. Observations made by PSP within and just outside the solar atmosphere show magnetic fields with distinctive switch-back structures that have been proposed as signatures of interchange reconnection (Figure 2-6).

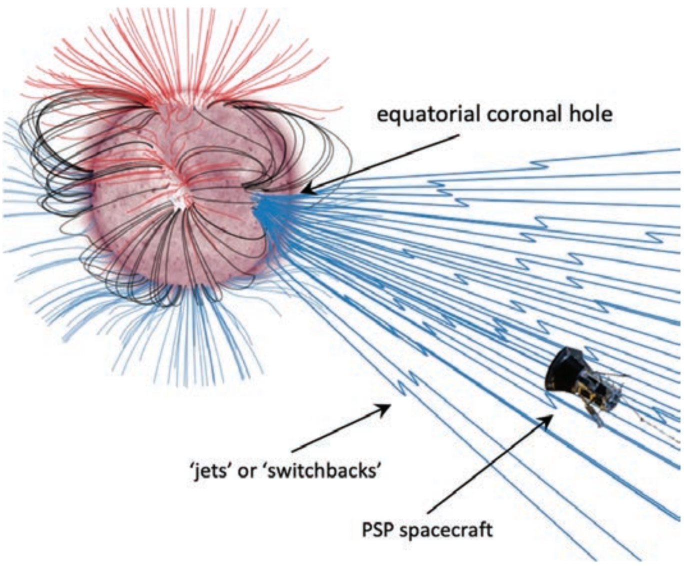


FIGURE 2-6 A major discovery of the Parker Solar Probe (PSP) was the occurrence of "magnetic switchbacks," unexpected rotations of the solar magnetic field. These rotations are more frequent closer to the Sun—in the accelerated solar wind above the Alfvén critical surface—as the sharp bends unwind when the field propagates with the solar wind to the interplanetary space. These switchbacks reveal as yet unconfirmed evidence of the origin of the fast solar wind and interplanetary magnetic field in the solar corona. The several theories that have been proposed await confirmation from the continuing PSP mission to map them ever deeper into the atmosphere of the Sun and connect them to observed activity there.
SOURCE: S.D. Bale, S.T. Badman, J.W. Bonnell, et al., 2019, "Highly Structured Slow Solar Wind Emerging from an Equatorial Coronal Hole," *Nature* 576:237–242, https://doi.org/10.1038/s41586-019-1818-7, reproduced with permission from SNCSC.

These combined results indicate that energy released by this reconnection contributes in an important way to the heating and acceleration of the fast solar wind. These remarkable discoveries need to be explored further using in situ measurements of the solar wind, including measurements of the heavy ion composition. Ground-based instruments like the newly commissioned Daniel K. Inouye Solar Telescope and space-based EUV spectroscopic imagers, such as MUSE and EUVST, may constrain the role of interchange reconnection low in the solar atmosphere. Resolving solar surface activity requires magnetic field maps covering the full surface of the Sun, as enabled by either continuous measurements over a full rotation, and/or multipoint observations from several vantage points around the solar ecliptic.

Local Processes Driving Large-Scale Energy Transfer

The MMS mission provided the first observations of reconnection regions at Earth's magnetic boundary (the magnetopause) that resolved the electron physics in the electron diffusion region. Observations in this region have, for the first time, combined studies of reconnection, turbulence, and shocks, as the turbulent magnetosheath is sandwiched between the upstream bow shock and the reconnecting magnetopause. Furthermore, complementary observations from NASA's THEMIS and the European Space Agency's Cluster missions, together with simulation models, have demonstrated the important role that Kelvin-Helmholtz waves play in energy conversion at the boundary.

There are still major gaps in understanding how energy, momentum, and mass are distributed, as geospace comprises several interconnected complex systems that interact on a variety of spatial and temporal scales. Understanding the control parameters of the energy transport processes at the magnetospheric (and other) boundaries requires a systems approach that addresses the transport of energy in both directions over the global surface and accounts for the state of the solar wind as well as that of the magnetosphere. Such results are only achieved by multipoint measurements covering the relevant regions and at scales that address both the large-scale system changes and mesoscale structuring. These multiscale measurements are achievable by a combination of multispacecraft in situ measurements, magnetospheric imaging, and numerical simulations capable of resolving mesoscale and ion-scale processes.

Role of Transition Regions in System Coupling

This focus area has two related topics: From Cool Neutrals to Hot Plasmas and Mesoscale Dynamics Within the Magnetosphere's Transition Regions.

From Cool Neutrals to Hot Plasmas

The upper atmosphere's mesosphere, thermosphere, and ionosphere are the layers where the neutral atmosphere is rarefied, ionized, and transformed in a continuous fashion into the near-space environment. Processes in this region are tightly coupled to the space above, through field-aligned currents, electrodynamic waves, feedback mechanisms, particle precipitation from the magnetosphere, and ionospheric outflow into outer space.

The ionospheric electron and ion density, plasma temperature, and plasma drifts are inferred by incoherent and coherent scatter radars (e.g., Millstone Hill, the Poker Flat Incoherent Scatter Radar [PFISR], and the Resolute Bay Incoherent Scatter Radar [RISR]), while plasma drifts are measured by incoherent scatter radars at mesoscales and by coherent scatter radars (e.g., the Super-Dual Auroral Radar Network [SuperDARN]) at larger scales. The auroral occurrence and dynamics are recorded by all-sky imagers, and ground-based magnetometer networks give a view to the horizontal electric currents in the ionosphere. In the next decade, the constellation formed by NASA's GDC and DYNAMIC missions will make multiplane, multialtitude observations that bring critically needed information about the upper atmosphere system inputs in the regions connecting to the space environment.

Mesoscale Dynamics Within the Magnetosphere's Transition Regions

The nightside transition region in the magnetosphere plays a key role in cross-domain and cross-scale coupling within geospace (Figure 2-7). This region connects the inner magnetosphere, dominated by Earth's dipole magnetic field, to the more distant plasma sheet where the magnetic field is stretched to form the magnetotail. The solar

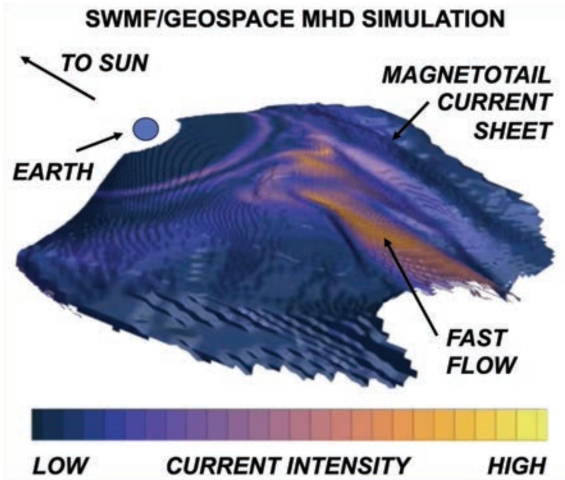


FIGURE 2-7 A Space Weather Modeling Framework (SWMF)/geospace magnetohydrodynamic (MHD) numerical simulation illustrating mesoscale structures in the magnetotail plasma and current sheet—that is, the transition region. During magnetospheric activity, the current sheet is folded, and flows are concentrated to mesoscale flow channels that wax and wane in rapid succession. Individual fast flows have been identified in space-based observations; however, no mission has determined the extent of the flow channels through the tail.
SOURCE: Courtesy of Matti Ala-Lahti, University of Michigan.

wind plasma and energy entering the magnetosphere through nightside reconnection are transported through the transition region and are ultimately deposited in the ring current, radiation belts, and the upper atmosphere, or flow around to the dayside along the flanks. All these energy flow pathways go through the transition region and are essential to system-wide geospace dynamics.

A significant fraction of plasma and magnetic flux transport in the nightside magnetosphere occurs in the form of bursty bulk flows. The bursty flows are mesoscale phenomena with cross-tail size of 1 to a few Earth radii. This cross-tail structure of the transition region has critical implications for how energy and magnetic flux are delivered into the inner magnetosphere, how the ring current and radiation belts are built up via particle injections, how energy and momentum are deposited in the upper atmosphere across different scales, and how these phenomena are reflected in a variety of mesoscale auroral forms. Much of the current observational knowledge about the transition region and its interaction with the upper atmosphere has been derived from fortuitous, but rare and ad hoc, multispacecraft conjunctions (e.g., THEMIS mission, Van Allen Probes mission, MMS mission, Geotail satellite, Los Alamos National Laboratory geostationary satellites, Geostationary Operational Environmental Satellites [GOES], and the Japanese Arase mission), space-based imaging (Two Wide-angle Imaging Neutral-atom Spectrometers [TWINS] and Imager for Magnetopause-to-Aurora Global Exploration [IMAGE]), and ground-based facilities (e.g., SuperDARN, riometers, all-sky imagers). However, the current spacecraft fleet is not sufficient to resolve the cross-tail structure of the transition region. In the absence of comprehensive observational evidence, models have provided key insights into the importance of the transition region for the coupled geospace dynamics (Figure 2-7); for example, models suggest that ring current and radiation belts may be substantially built up by mesoscale flows and particle injections. However, the ability to cross-check the models with observations is hampered by the lack of observational coverage at mesoscales. Furthermore, the physics of the transition region has proven particularly challenging for models because it is where fast flows, particle drifts, and ion gyro-radius effects are all important.

Studies of the transition region will be a major focus in the next decade. Addressing the physics of the transition region and its role in cross-domain and cross-scale geospace coupling will require a coordinated systems-level effort combining sufficiently resolved multipoint in situ measurements of the magnetosphere and imaging of the magnetosphere and ionosphere, a network of ground-based observatories equipped with comprehensive instrumentation to monitor the upper atmosphere system, and new models addressing the challenging transition region physics (e.g., models based on "beyond-magnetohydrodynamic [MHD]" approaches) and its coupling with the upper atmosphere. Improvements in simulation, data science, and assimilation methods, and the associated computational resources would enable a self-consistent treatment of the transition region in the models. Furthermore, to understand how magnetospheric processes influence and are influenced by the dynamics and state of the upper atmosphere system, NASA's GDC and DYNAMIC's multiplane, multialtitude constellation will bring critically needed information about the upper atmosphere system in the regions that connect to the mesoscale processes at work in the transition region.

This focus area has two related topics: Explosive Processes Traversing the Sun's Transition Region and Waves at the Transition Layer.

Explosive Processes Traversing the Sun's Transition Region

The Sun's atmosphere undergoes several distinct transitions above its visible surface, the photosphere, which is a largely neutral, hot gas with a temperature of nearly 6,000 K dominated by gas motions. The chromosphere is sensitive to impacts of magnetic energy release in the low corona that accelerate electrons, which, when streaming to the chromosphere, lead to heating, ionization, radiation, and dynamical expansion. NASA's Interface Region Imaging Spectrograph (IRIS), SDO, Nuclear Spectroscopic Telescope Array (NuSTAR), Japanese HINODE, and the Goode Solar Telescope (GST) have contributed new insights on how the solar plasma is heated and how even the smallest magnetic energy release events—nanoflares—have observable signatures in the chromosphere. These new insights help constrain the role of nanoflares in energy budget of the low solar atmosphere.

Open questions remain concerning the energetics and dynamics as well as processes that lead to thermal and magnetic structuring of the chromosphere. In the next decade, Inouye will provide extraordinarily detailed new observations of the magnetic field and plasma dynamics in each of these regions. Complementary space-based and ground-based instruments, from radio to X-ray wavelengths, are needed to work in concert with Inouye to observe these transitions from a systems perspective.

Waves at the Transition Layer

Optical observations of the aurora capture the excitation of atmospheric atoms and molecules by high-energy particles from the magnetosphere and the solar wind. Two recent discoveries both highlight previously unknown transition layer dynamics: Dune aurora between the atmosphere and ionosphere reveals a wavy structure in the atmospheric density at auroral altitudes, thereby connecting atmospheric neutral gas and space plasma processes. The formation mechanism of such an unusual, horizontal auroral structure is not known. At another transition layer, between the auroral region and the lower-latitude sub-auroral region, STEVE (Strong Thermal Emission Velocity Enhancement) were observed but defy categorization as either traditional aurora or airglow (Figure 2-8).

Auroral imaging, complemented by energetic neutral atom imaging of the tenuous magnetosphere, provides a comprehensive view of the full range of dynamical processes in the coupled magnetosphere–ionosphere system. Auroras are routinely observed by ground-based all-sky imagers. However, the all-sky imagers are limited by clouds that obstruct the observations, and by the shape of Earth, which limits the field of view of a single camera to about 600 km. Addressing key science questions for the next decade related to mesoscale structuring and coupling to the adjacent layers and regions will require having continuous imaging of the entire auroral regions, extending to midlatitudes, and preferably over both poles.

2.1.3 Guiding Question: How Do the Components of the Sun–Earth System Interact with Each Other?

By the time the solar wind flow reaches the outer heliosphere, the solar magnetic field that is carried out with the wind wraps around the Sun and forms a tightly bound spiral. This spiral is disturbed by large solar eruptions that create both energetic particle bursts and plasma clouds that reach the outer fringes of the solar system. The ability of the magnetic field to guide and accelerate particles makes it a primary mediator of interactions between

FIGURE 2-8 The recently discovered subauroral form named STEVE (Strong Thermal Emission Velocity Enhancement) is formed through a yet unknown interaction between the neutral atmosphere and the ionosphere.
SOURCE: Courtesy of Edwina Podemski, Cline River Photography.

the system parts. This mediation is as active at the heliospheric boundary as it is closer to the Sun where the interplanetary field interacts with the planetary magnetospheres.

Space plasmas are complex systems that have nonlinear feedback and interactions. Moreover, the heliosphere has several energy sources—the most significant being the Sun—but also including locally important planetary dynamos, planetary rotation, and tectonic activity—that drive dynamic processes that couple with those driven by the Sun. The multiple energy sources, combined with the nonlinearities in the physical laws guiding the field and plasma evolution, make the system theoretically difficult, while the vast system size and structuring in all spatial and temporal scales make it observationally challenging. However, the local space environment is the only place where detailed plasma measurements are made in systems not limited by artificial boundaries.

Magnetic Connections Across the Heliosystems

This focus area has only one related topic: Magnetic Fields as Connectors.

Magnetic Fields as Connectors

In one much-studied but still poorly quantified example, the terrestrial magnetic field acts as an invisible link between the magnetosphere and ionosphere. At lower latitudes, Earth's dipolar magnetic field couples the two hemispheres to each other, while the higher-latitude ionosphere is coupled to more distant parts of the magnetosphere. Thus, the magnetic field creates a mapping between ionospheric and magnetospheric processes, and between processes in the two hemispheres.

Observational determination of the mapping is exceedingly difficult, especially in the magnetotail, where the magnetic field is both dynamically varying and highly stretched, mapping a vast volume in the magnetotail to a tiny spot in the ionosphere. Closer to Earth, where the field is still quasi-dipolar, some success has been achieved leveraging the discovery of high correlation of magnetospheric chorus waves with pulsating aurora (see Figure 2-9). Statistical data-based empirical magnetic field models are widely used to establish magnetic mapping but contain significant uncertainties.

Accurate magnetic mapping is necessary to answer critical questions of magnetosphere–ionosphere coupling that range from revealing sources of the puzzling hemispheric asymmetries to connecting multiscale plasma sheet

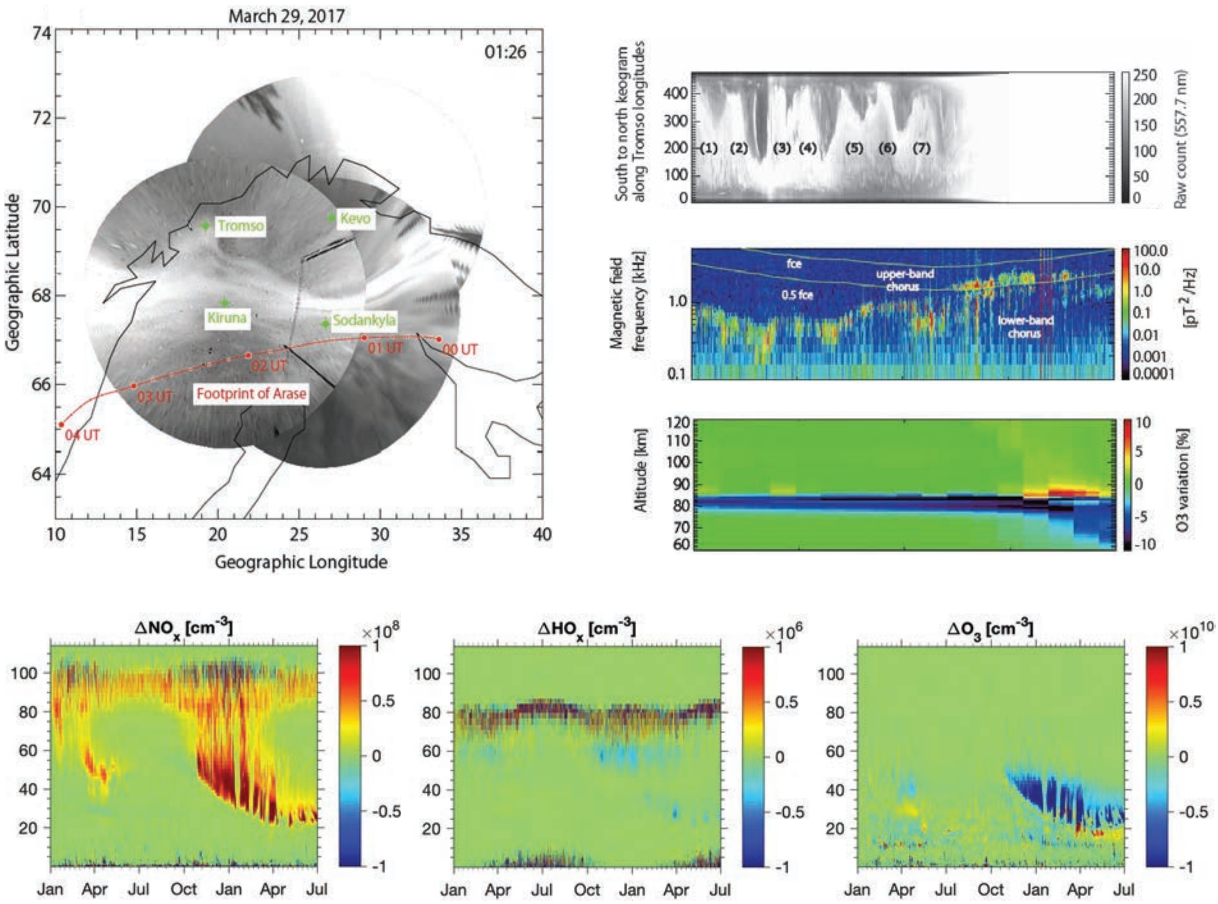


FIGURE 2-9 Pulsating auroras are caused by the intermittent electron precipitation driven by wave-particle interactions, for example, in the inner magnetosphere. There is a second effect of electron precipitation, namely catalytic depletion of ozone (panel f) at that altitude. As these processes occur daily, they influence the mesospheric ozone chemistry, thus coupling the space plasma processes to the neutral atmospheric chemistry.
SOURCES: *Top row:* Adapted from Miyoshi et al. (2021), https://doi.org/10.1038/s41598-021-92611-3. CC BY 4.0. *Bottom row:* Adapted from Verronen et al. (2021), https://angeo.copernicus.org/articles/39/883/2021. CC BY 4.0.

structures to their auroral counterparts. Magnetic mapping is especially important in the magnetotail transition region, where the magnetic field changes from quasi-dipolar to tail-like, and where many auroral forms are believed to have their origin. The transition region is often dominated by mesoscale flows, highly structured magnetic field features, and particle injections, which all drive field-aligned currents that couple to mesoscale auroral features in the ionosphere. The rapid variations within the transition region and the multiscale nature of those variations make both observing and physics-based modeling challenging, thus magnetic mapping remains elusive.

While magnetic mapping remains a challenge, it has been shown that auroral processes in the two hemispheres contain unexplained asymmetries. Such asymmetries arise from the position of the dipole field slightly away from the center of Earth, its inclination relative to Earth's rotation axis and to the ecliptic plane, and over shorter timescales from the orientation of the interplanetary magnetic field and solar wind flow. While it would be important to include such asymmetries in physics-based models, the lack of observations from the southern hemisphere limits the ability to quantify the asymmetries. Major advances in this area could be made by imaging the auroral distributions simultaneously over both hemispheres. Important synergy is achieved by combining these observations with observations of the ground magnetic field disturbances and field-aligned current patterns using existing observational capabilities such as those from SuperMAG and the field-aligned current patterns from the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) project.

Multiple Drivers and Feedback Mechanisms

This focus area has two related topics: Between the Heliosphere and Interstellar Matter and Between the Atmosphere and Space.

Between the Heliosphere and Interstellar Matter

Plasmas and magnetic fields in the interstellar medium act as a barrier to the expanding solar wind. At the same time, neutrals from the interstellar medium penetrate into the heliosphere, influencing its dynamic evolution (Figure 2-10). Local interstellar matter is a source for the heliosphere through a variety of processes, most notably pickup ions. New Horizons may reach these distances as soon as the next decade and thus bring new observational insights into their contribution.

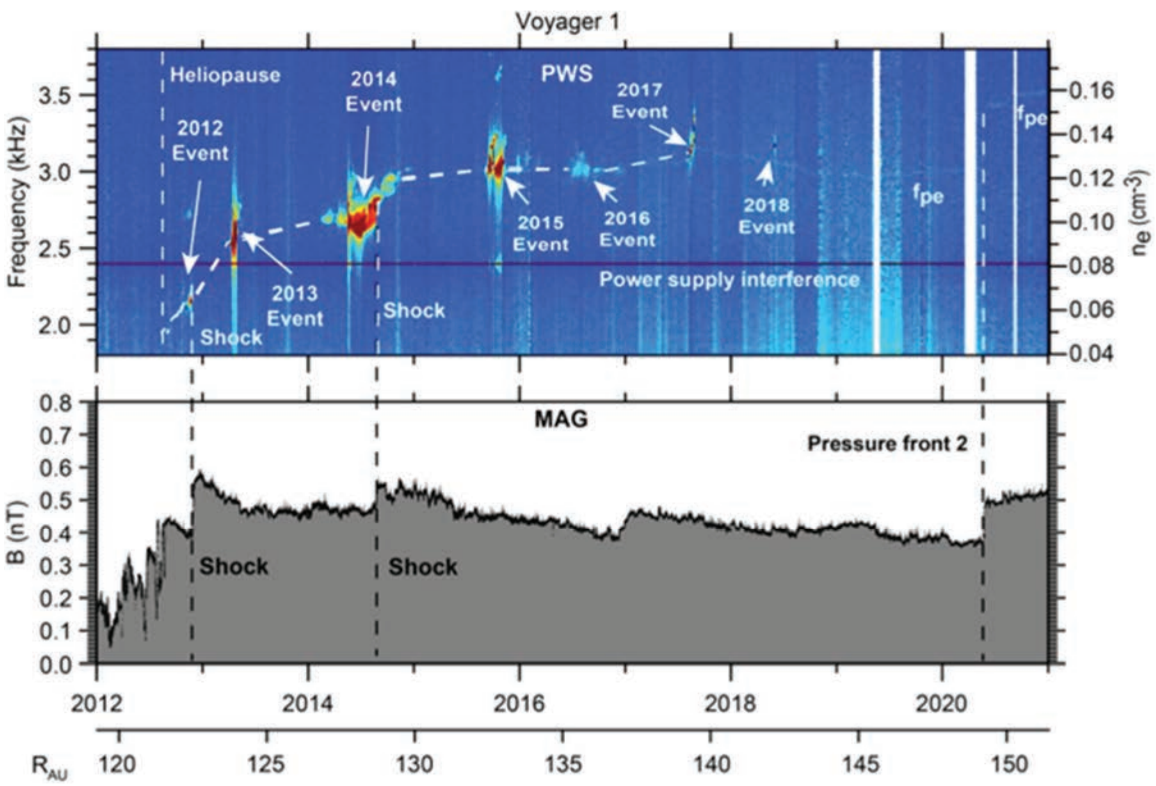


FIGURE 2-10 Voyager 1 (and 2) are now in a region where the dynamics is driven by both the heliosphere and the very local interstellar medium (VLISM). Over the 8-year period shown in the bottom graph, the magnetic field measured at Voyager 1 shows four distinct enhancements. The first two have been identified as shocks, and they are associated with enhancements of electron plasma oscillations (top graph) generated by shock-accelerated electrons. These features are likely associated with solar activity expanding into the VLISM. In contrast, later enhancements, such as the one in 2020, are identified as pressure fronts, where the magnetic field raises slower and there are no corresponding electron plasma oscillations. These fronts are thought to be driven by compressive waves generated by the interaction of heliosheath with the heliopause and then propagated through the VLISM, presumably interacting with one another to produce the results observed by Voyager 1.
SOURCE: Adapted from D.A. Gurnett and W.S. Kurth, 2019, "Plasma Densities Near and Beyond the Heliopause from the Voyager 1 and 2 Plasma Wave Instruments," *Nature Astronomy* 3:1024–1028, https://doi.org/10.1038/s41550-019-0918-5, reproduced with permission from SNCSC.

Heliospheric plasmas are permeated by solar magnetic fields that connect distant parts of the system via waves and particles propagating along the field. Understanding the physical processes that shape the heliosphere, including the heliosheath between the local interstellar matter and the heliospheric boundary, is a key challenge for the next decade that requires both remote and in situ observations of the processes at the boundaries. Remote observations are provided in this decade by IBEX and IMAP. Key challenges are to keep receiving the invaluable observations from the New Horizons and Voyager spacecraft, which are the only means to gain firsthand knowledge of the environment in the outer heliosphere and outside the heliospheric bubble.

Between the Atmosphere and Space

The ionosphere is not a passive recipient of dynamics driven by the magnetosphere and the solar wind. Rather, it plays an active, variable, and, at times, crucial role in many magnetospheric processes. In the ionosphere, the electric conductance, electric field, and field-aligned currents to and from the magnetosphere are combined to a complex nonlinear system with feedback processes. For example, charged particles carrying field-aligned currents increase the local conductance, which then allows for stronger current flow into the ionosphere. While the AMPERE project provides semi-continuous monitoring of the field-aligned currents at the global scale, there are currently no direct ways to resolve the regional (mesoscale) field-aligned current systems or the fine conductivity structures they create and that are critically important for the ionospheric energy dissipation processes.

Measurements of field-aligned currents are crucial for characterization of the electrodynamics within auroral forms that couple to the magnetotail. Such forms include auroral streamers associated with magnetotail bursty bulk flows or the westward-traveling surge forming at the onset of explosive magnetic field reconfiguration during substorms. Determining these key parameters for magnetosphere–ionosphere coupling requires measurements of the time-variable neutral density and composition and particle precipitation from the magnetosphere (and solar wind). The upcoming Electrojet Zeeman Imaging Explorer (EZIE) will characterize the structure and dynamics of the auroral electrojets flowing in the lower ionosphere, resolving some of the intense mesoscale horizontal currents in the magnetosphere–ionosphere system.

The ITM system changes over longer timescales as it responds to persistent changes in the lower atmosphere, of both natural and anthropogenic origin. Changes in the density of the thermosphere on multidecadal timescales have been observed, but it is not known what other consequences such slow composition variations may have, or how these variations may affect the response of this region to the solar wind and magnetospheric processes. Furthermore, it is not known how the changes in the lower atmosphere weather systems will alter the relative impact of the solar variability.

2.1.4 Sun–Earth–Space: Our Interconnected Home—Theme 1 Synopsis

Observing the entire Sun–Earth–Space system is challenging. The vast volume must be covered over a wide range of spatial scales to resolve processes from microscales to the system size, and temporal scales from fractions of seconds required by turbulence and wave-particle interactions to solar cycle decadal timescales needed to understand the solar dynamo. Major progress in understanding this interconnected system is achieved by imaging Earth's space environment with newly developed technologies as well as utilizing both ground- and space-based platforms that provide in situ plasma and remote sensing measurements from many vantage points at scales not resolved previously (Table 2-1).

Because the ground- and space-based observing network will remain sparse in the vast interconnected heliosphere, great advances in data science, data assimilation, physics-based and empirical models and simulations, as well as artificial intelligence (AI), machine learning, and computer vision techniques, are needed to make full use of the available heterogeneous observations. Increases in the computational capacity—including transition to exascale, heterogeneous computing, hundreds of petabytes of storage, AI-optimized hardware, and cloud computing capabilities—hold promise for vast amounts of observations and more accurate, larger numerical models that can describe more of the individual system processes than was possible before. Data assimilation, ensemble modeling, and machine learning methods are needed to assess the state of the system and the most probable temporal evolution requires calibration across the heterogeneous instrument suite.

TABLE 2-1 Sun-Earth-Space: Our Interconnected Home—Theme 1 Guiding Questions, Research Focus Areas, Observations, and Modeling Needed to Carry Out the Research

Guiding Question	Focus Areas	Observation Needs	Model Needs
How does our heliosphere function as a nested system?	• Energy and momentum flow across and within the heliosystem parts • Dominant physical processes within system interactions • Interactions across large-scale regions and long timescales	*Heliosphere:* Remote sensing and in situ observations from a range of vantage points. *Magnetosphere:* Multispacecraft plasma and field measurements with remote sensing capabilities. *Upper atmosphere:* Multiplane, multialtitude plasmas and fields, neutral densities, neutral winds, and atmospheric waves.	Large-scale, integrative heliospheric systems models
How do heliosystem boundaries manifest themselves?	• System impacts of magnetic boundary processes • Role of transition regions in system coupling • Interactions at plasma-neutral transition regions	*Heliosphere:* Magnetic field, plasma state and dynamics, and energetic particles at different layers of the solar atmosphere and throughout the heliosphere. *Magnetosphere:* Combination of multispacecraft in situ measurements, magnetospheric imaging, and numerical simulations. *Upper atmosphere:* Multiplane, multialtitude measurements of the auroral outflow processes, including plasma and neutral components.	Detailed plasma physics and neutral gas models covering a variety of scales and processes from kinetic to large-scale coupling
How do the components of the Sun–Earth system interact with each other?	• Magnetic connections across the heliosystem • Multiple drivers and feedback mechanisms	*Heliosphere:* Plasmas, energetic particles, and fields in the inner and outer heliosphere *Magnetosphere:* In situ multipoint mesoscale resolving magnetic field and plasma measurements from magnetotail transition region combined with auroral and ionospheric plasma remote sensing observations. *Upper atmosphere:* Simultaneous observations of auroral and ionospheric processes at both hemispheres	Large-scale, integrative heliospheric systems models combined with models covering one or a few of the systems with capability to resolve smaller mesoscale processes that have large-scale impacts.

2.2 THEME 2—A LABORATORY IN SPACE: BUILDING BLOCKS OF UNDERSTANDING

The space around the planets and the Sun hosts myriad physical processes, many of which remain poorly understood. The local cosmos is largely accessible for studying the physics of these processes. These fundamental processes occur throughout the universe and locally, giving rise to some of the most spectacular and intriguing phenomena in the solar system. For example, the solar sunspot cycle is inexorably linked to the interior solar dynamo. Solar activity, driven by this dynamo, is responsible for effects throughout the heliosphere. These effects include, for example, the extreme variability of Earth's magnetosphere and ionosphere, cosmic ray modulation, and propagation of shocks and pressure waves into the very local interstellar medium. Thus, understanding the solar dynamo is key to understanding solar activity and geomagnetic variability. It is now known that other stars exhibit cyclic behavior, and therefore the generation of magnetic fields in stars is a fundamental, universal process. By inference, the cyclic behavior in stars must drive variability in exoplanet magnetospheres and ionospheres.

Another fundamental process is cross-scale coupling in plasmas. This coupling connects the microscale with all other scales in a plasma. Nowhere is this connection more apparent than in explosive magnetic reconnection (where "explosive" implies an instability growth time that is short compared to the timescales of other transport or interaction processes). The MMS mission has provided a deep understanding of the electron-scale microphysics of reconnection. What remains to be understood is how this turbulent and often highly variable process couples across many scales to produce large-scale, coherent structures like the explosive substorm reconnection process in the magnetotail. Understanding this cross-scale coupling process is key to understanding the magnitude and extent of variability in Earth's magnetosphere and, by inference, variability in exoplanet magnetospheres. Theme 2—A Laboratory in Space: Building Blocks of Understanding is prioritized into three guiding questions (see Figure 2-11). Each guiding question comprises several focus areas, where significant progress is achieved in the next decade. Each guiding question and its respective focus areas are discussed in sequence in this section.

Last, the intermingling of ionized and neutral gasses is ubiquitous in planetary atmospheres and magnetospheres, the interplanetary medium, and in a wide variety of other regions throughout the universe. The nature and consequences of the coupling between ionized and neutral gases are only now beginning to be understood.

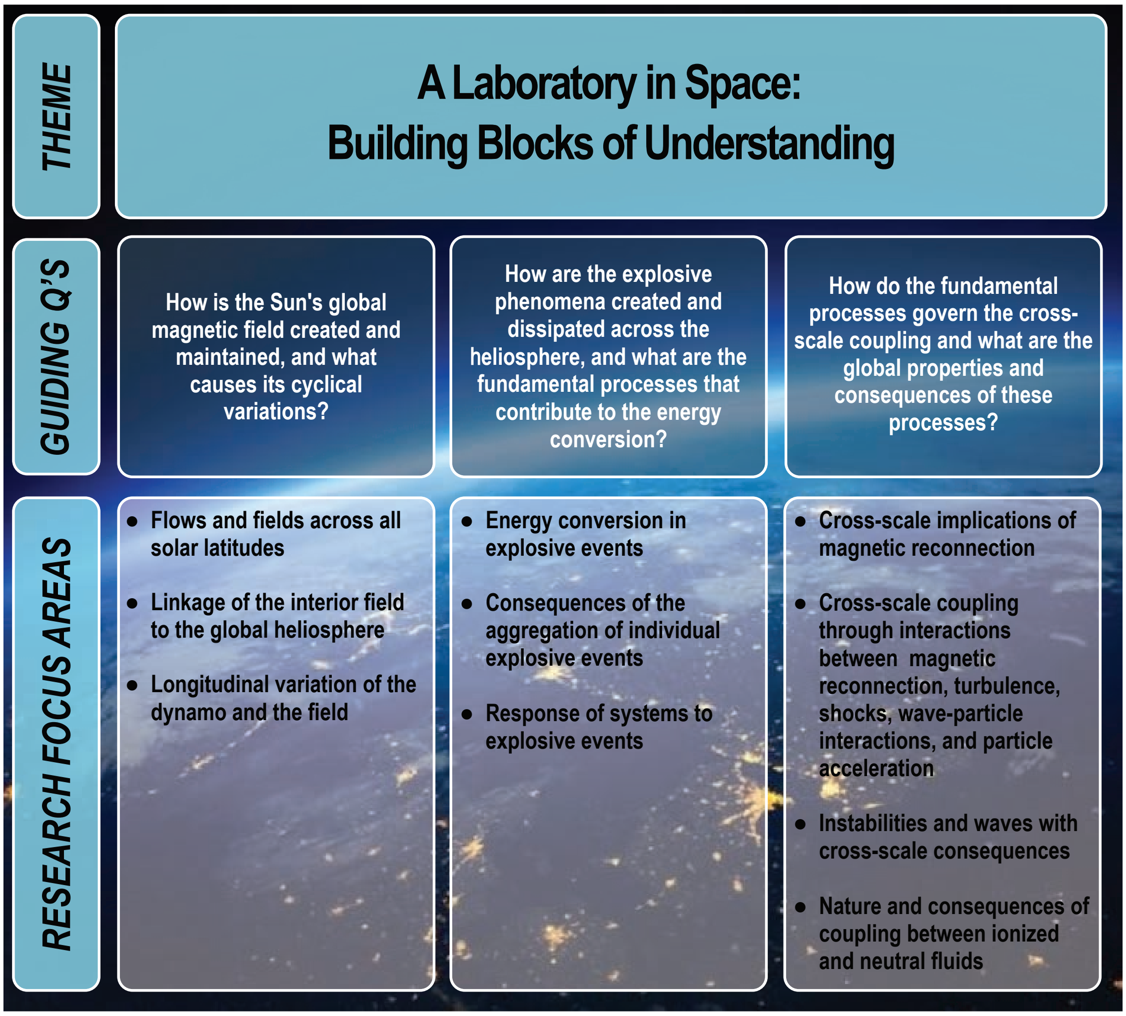


FIGURE 2-11 Guiding questions and research focus areas within Theme 2—A Laboratory in Space: Building Blocks of Understanding. Significant progress on these focus areas is made in the next decade through the comprehensive, balanced research strategy described in Chapter 5.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Background image from IM_photo/Shutterstock.com.

This coupling is extraordinarily complex in Earth's upper atmosphere where the forcing on the region comes strongly from the magnetosphere above as well as from the lower atmosphere below. Understanding this complex interaction has the promise for application to other ionospheres and atmospheres such as those of Jupiter, Saturn, Uranus, and Neptune. In the context of the interplanetary medium, neutral gas, predominantly hydrogen, flows through the solar wind experiencing charge exchange and creating interstellar pickup ions that form the dominant thermal plasma component from about 20–30 astronomical units (AU) until the heliospheric boundary, the heliopause. A fraction of the pickup ion population is further energized to form the anomalous cosmic ray population. Indeed, pickup ion dynamics created via neutral interstellar gas are now recognized as one of the most important dynamical elements in determining the physics, size, and scale of the large-scale heliosphere. These and other fundamental processes have been a subject of a wide variety of investigations. Owing to their key role as building blocks of dynamical behavior, the solar and space physics system requires an understanding of these fundamental processes. Owing to their universality, an understanding of these fundamental processes holds the promise of deeper understanding of other environments.

While these fundamental processes are present throughout the universe, they are best studied where they are observed in situ. Many of the neutral gases and plasma regions in the local cosmos are readily accessible to spacecraft and suborbital assets. Furthermore, the relative closeness of these regions enables unprecedented temporal and spatial resolution using ground-based, suborbital, and space-based remote sensing assets. In the next decade, a new generation of instruments on the ground and in space, combined with the next-generation modeling, will revolutionize the understanding of building blocks of heliosystems.

2.2.1 Guiding Question: How Is the Sun's Global Magnetic Field Created and Maintained, and What Causes Its Cyclical Variations?

One of the main factors creating the local space environment, coupled across the solar system, is the interior dynamo generating the Sun's magnetic field. Dynamos are ubiquitous in the universe, generating magnetic fields in any astronomical body with a turbulent, electrically conducting fluid, including Earth, planets, and at least one moon in the solar system, as well as other stars, planets, accretion disks, and even galaxies. The Sun is the best example in which to study the universal process of stellar dynamos. Owing to its critical role in the solar system, the solar dynamo process has been a subject of study for over a century. The roughly 22-year cycle sets the rhythm of space weather, dictating the years with large flares and eruptions, and modulating the cosmic ray flux coming into the solar system.

Research into the Sun's interior over the previous decade has produced many notable discoveries. Helioseismic measurements continue to yield an ever-clearer image of the flows inside the Sun, including subtle meridional flows and a previously undetected inertial mode known as a Rossby wave. Numerical models are growing in sophistication and fidelity and have shown differential rotation, periodic polarity reversals, aspects of torsional oscillations, and the so-called butterfly diagram. Empirical models are now sufficiently accurate to be useful for space weather forecasting. These models make use of parameterized flows, including meridional circulation cells assumed to extend toward the solar poles, and returning equatorward at some depth below the surface.

Flows and Fields Across All Solar Latitudes

Despite progress to date, the highest latitudes of the Sun remain terra incognita. Previous observations did not resolve either the structure or the dynamics of the polar regions. The current understanding of solar low- and mid-latitude processes has raised new compelling questions about the high-latitude regions. These questions need to be answered because the low-, mid-, and high-latitude regions are strongly coupled. Advances in numerical simulation point to the crucial role played by the poles in the operation of the global dynamo. Meridional flows are observed to move magnetic flux poleward, but the observations made to date do not show where these flows subduct, leaving the flux to reverse at some yet unknown latitude. Models have these flows subducting at or near the poles and returning at some hypothesized depth. Recent developments in empirical modeling have made clear that this reversal process is critical to setting the amplitude and timing of the Sun's 22-year cycle. The subduction remains largely unobserved from the ecliptic vantage point. Measuring this subduction and return flow is critical to understanding the solar dynamo, which is also critical for improving the ability to forecast solar activity.

Other rotating atmospheres, including those of Jupiter (as revealed by Juno) and Saturn (as revealed by Cassini), show organized vortices in their polar regions. It is not clear if the Sun has similar polar structures. Evidence for the presence of vortices in the polar regions of the Sun will reveal the relation between rotation and convection and inform dynamo models. There is tantalizing evidence that the magnetic network at high latitude includes stronger fields than the network seen directly from the ecliptic. Simulations also show that different dynamo regimes produce flows that are clearly distinguishable from a polar perspective (see Figure 2-12). This final piece of the global dynamo puzzle is answered using direct observations of the flows and magnetic fields in the Sun's polar region.

Linkage of the Interior Field to the Global Heliosphere

The magnetic field anchored at the Sun's high latitudes plays a crucial role in the formation of the heliosphere. Extrapolating from the surface field that is observed from the ecliptic leads to a prediction of open magnetic flux. Therefore, the heliospheric field above the corona out to 1 AU and beyond is predicted to be significantly weaker than what is observed in situ. This "open-flux problem" cannot be addressed, much less solved, until the magnetic fields at the poles are observed directly. Until this is done, the understanding of the heliosphere, even in the ecliptic, remains incomplete and speculative. In addition, the uncertainty that the open-flux problem creates in

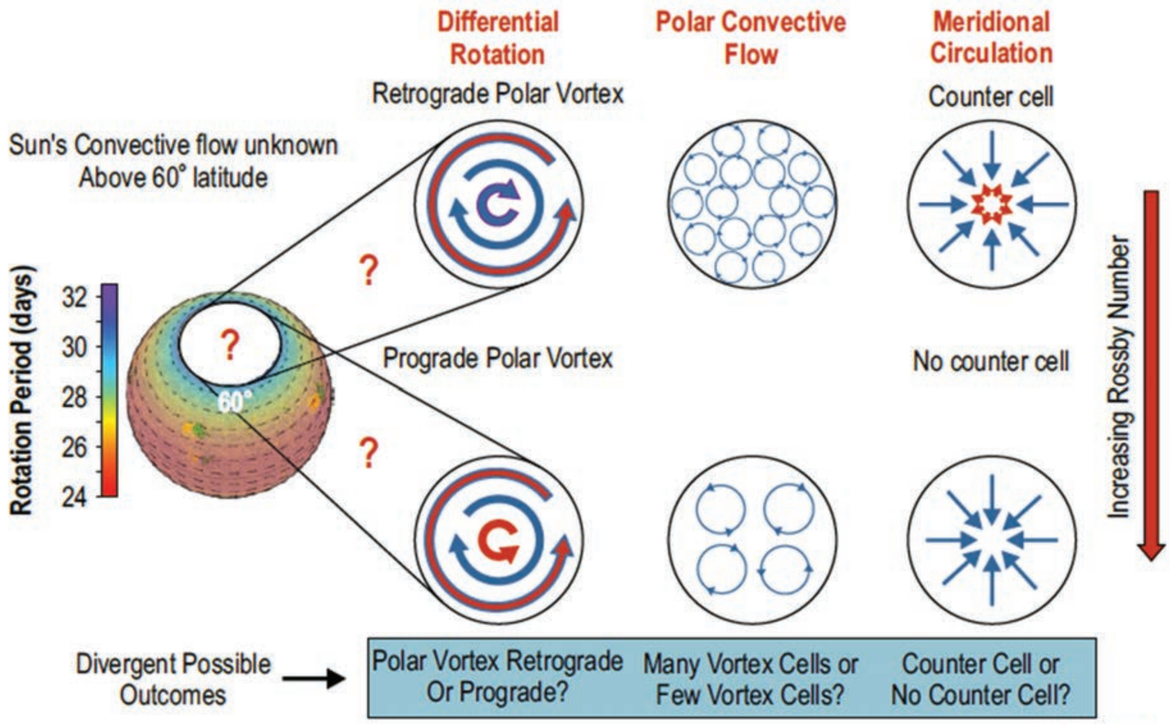


FIGURE 2-12 The global velocity structure of the Sun as it is currently known (left) and hypothesized structures of the region above 60° latitude, which are currently unconstrained by direct observations. Depending on the physics governing the flows, poorly known at present, these may or may not include a counter cell driving away from the pole, small or large convective flows, and a polar vortex circulating in either direction (retrograde or prograde). These divergent predictions for the polar regions motivate the need for measurements of the polar regions of the Sun.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute. Compiled from Hassler (2023), https://baas.aas.org/pub/2023n3i164/release/1. CC BY 4.0; Baldner (2023), https://doi.org/10.3847/25c2cfeb.f8b34dc8. CC BY 4.0.

the determination of the heliospheric magnetic field is a major detriment to space weather prediction capabilities because this field is a critical input into heliospheric models.

Longitudinal Variation of the Dynamo and the Field

The dynamo is known to produce a magnetic field with clear longitudinal variation on timescales less than a solar rotation. The view from one perspective in the ecliptic (i.e., along the Earth–Sun line) does not reveal the full longitudinal structure of the field. Nor does this single perspective help explain if the variation is the result of symmetry breaking in a dynamo with mostly axisymmetric flows, or if the flows themselves are asymmetric. Insight into the full longitudinal structure of the dynamo, its fields, and the heliosphere it creates is gained by measuring the flows and magnetic fields from multiple vantage points.

2.2.2 Guiding Question: How Do Fundamental Processes Create and Dissipate Explosive Phenomena Across the Heliosphere?

Space plasmas and neutral gasses across the solar system are hosts to sudden explosive events in which energy is rapidly converted from one form to another. Such phenomena include solar flares, geomagnetic storms and substorms, CMEs, bursty magnetotail convection, and atmospheric waves launched by volcanoes. The events themselves are fundamental to determining the state and time evolution of that particular system. Each kind of explosive event, however, occurs through the combined action of fundamental processes found throughout the solar system and beyond. Energy release and conversion occurs through the processes of magnetic reconnection, shocks, waves, turbulence, and particle acceleration. These universal processes remain the focus of study for space-based missions, ground-based facilities, and laboratory plasma experiments. It is only through these studies that explosive events and their consequences can be understood.

In the previous decade, coordinated observations by IRIS, RHESSI, SDO, Hinode, and EOVSA, among others, have revealed new details about the energy release process at work in solar flares. Upcoming observations by MUSE, able to make spectroscopic and imaging measurements simultaneously at high temporal cadence, promise to reveal still more about flares. MMS has observed in situ the energy release by magnetic reconnection in Earth's magnetosphere, while THEMIS and other magnetospheric spacecraft and ground assets have observed the consequences of explosive reconnection throughout the magnetosphere. The unprecedented spatial resolution of MMS measurements has revealed the inner workings of energy thermalization within the small-scale region where magnetic reconnection "decouples" charged particles from magnetic field lines.

Energy Conversion in Explosive Events

Magnetospheric substorms and solar flares are prototypical examples of explosive events. Each occurs when stored magnetic energy is released by magnetic reconnection and converted into other forms. The understanding of many aspects of this process has improved through observations, theory, and modeling over the past decade; however, many crucial questions about these aspects remain unanswered. Key to understanding the energy output of explosive events are answers to questions such as, How much of the magnetic energy stored in advance is actually released? What fraction of the released energy is converted into bulk kinetic energy, waves, heat, or energy to non-thermal particles? How does a reconnection region form and evolve? and What is the interplay between reconnection, turbulence, and shock dynamics? Importantly, a portion of this energy both from solar flares and from substorms is deposited into Earth's atmosphere either through electromagnetic energy transport or thorough particle precipitation.

Consequences of the Aggregation of Individual Explosive Events

The combination of individual explosive events plays a critical, and still poorly understood, role in structuring and establishing the state of plasma systems throughout the solar system. For example, frequent, small-scale flare-like energy releases, called nanoflares, are believed to be responsible for establishing the temperature and density of the Sun's corona. The largest solar flares and CMEs constitute a population of events that may play a collective role in structuring the global heliosphere. Small-scale interchange reconnection events play a role in accelerating and structuring the fast solar wind. Mesoscale reconnection events and the resulting plasma flows and injections may contribute to the generation of large-scale current systems (e.g., the substorm current wedge) and to the buildup of the ring current in Earth's magnetosphere. Understanding the structuring of plasma systems from these example aggregations of small-scale and mesoscale events is a focus in the next decade.

Response of Systems to Explosive Events

A plasma or fluid system changes state in response to the impulsive driving from an explosive event. Studying the impulse response of a system is a widely recognized technique for studying a system itself. Advances in observations, theory, and modeling over the previous decade have opened the possibility to apply this technique with greater effect to systems across the heliosphere. The Sun's photosphere and lower chromosphere is observed in exquisite detail, especially from the ground using, for example, the Inouye Solar Telescope. The response of these layers to the coronal energy released by a flare is a fruitful means of studying these layers as well as the energy release process itself, which has yet to be fully explored.

Explosive events in the terrestrial magnetosphere often occur in response to solar wind driving. The solar wind energy enters Earth's magnetosphere through a series of boundaries such the bow shock and the magnetopause, which involves dissipative processes that allow the solar wind mass, momentum, and energy to be transported and energized across the boundaries. The entire geospace system responds to explosive events such as geomagnetic storms and substorms, from the global reconfiguration of the magnetosphere to impulsive and spatially structured current closure and energy deposition in the ionosphere manifested in spectacular auroral displays. Studying the system as a whole, filling in the gaps in the observations with theory and modeling, is key to progress in the next decade.

There is a basic understanding of the degree to which Earth's upper atmosphere (ITM) system responds to impulsive driving by geomagnetic storms and solar flares from above and tsunamis, tornadoes, volcanic eruptions (Figure 2-13), and human-caused explosion events from below. Future constellation satellite missions, starting with GDC and DYNAMIC, in coordination with ground-based observations, will enable a systems science approach to

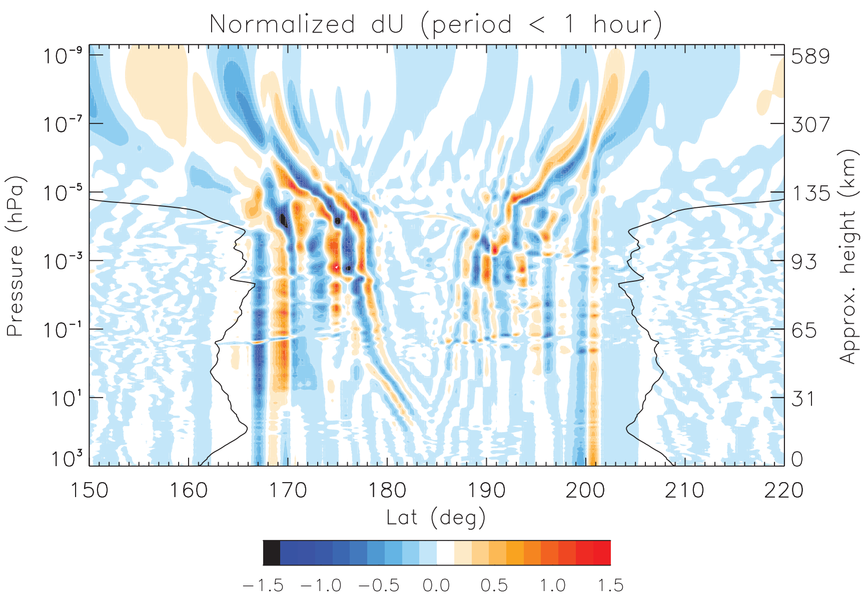


FIGURE 2-13 The WACCM-X (Whole Atmosphere Community Climate Model with Thermosphere and Ionosphere Extension) simulated zonal wind amplitude at 20.5°S and 175°W, at UT 06:05 hours owing to the Hunga-Tonga volcano eruption. Vertical profiles: propagation distance from the epicenter of the Hunga-Tonga volcano eruption with the local acoustic speed for each altitude. This simulation demonstrates the response of the atmospheric system to explosive forcing from the lower atmosphere. SOURCE: Liu et al. (2023), https://doi.org/10.1029/2023GL103682. CC BY 4.0.

determine the mechanisms of energy and momentum transformation/exchange during and after extreme events. This line of research will also quantify the most important salient factors governing the global ITM response during and following geomagnetic activity.

2.2.3 Guiding Question: How Do Fundamental Processes Govern Coupling Across Spatial Scales?

In the past decade, heliophysics missions have opened an unprecedented era of high-resolution observations in the near-Earth space and in the laboratory on Earth, leading to major progress in understanding the microphysics governing shocks, magnetic reconnection, turbulence, and wave–particle interactions, as well as neutral and plasma coupling. MMS has observed magnetic reconnection with unprecedented detail, making clearer the individual roles played by ions and electrons at disparate scales. At the same time, theory and modeling and laboratory plasma experiments have contributed significantly to the understanding of the microphysics by providing predictions for, and explanations of, the complex observations. However, these advances have also revealed important open questions—notably missing is the global context and impacts of this kinetic physics. It is not well understood how large-scale conditions control microscale processes, how the microscale processes impact the global dynamics, and how the interaction and feedback between the various scales operate. The understanding of how the fundamental plasma and neutral processes are coupled across multiple scales, as well as the global consequences of the processes, is crucial for applying the knowledge gained from studies of the solar system (from small magnetospheres at Mercury and Ganymede to the vast magnetosphere of Jupiter) and to astrophysical phenomena.

Cross-Scale Implications of Magnetic Reconnection

On Earth, magnetic reconnection is a dominant process that allows solar wind to enter the magnetosphere through magnetospheric boundaries. The entering solar wind energy ultimately drives geomagnetic storms, substorms and ionospheric dynamics such as auroras. Ultra-high-resolution and small-spatial-scale observations of reconnection regions made in the previous decade have led to major breakthroughs in the understanding of how magnetic field lines are able to break and reform at the reconnection site, explosively releasing magnetic energy into particle acceleration. Further examples are found in planetary magnetospheres such as reconnection in the magnetotail of Jupiter that leads to release of material down the tail in plasmoids (as observed by Galileo, New Horizons, and Juno).

Reconnection plays a critical role creating, structuring, and possibly heating the Sun's corona. Remote sensing observations have revealed this process on ever smaller scales, although still far larger than the capability of in situ measurements. Reconnection is also implicated in the ongoing, sporadic exchange between the closed coronal field and the open solar wind. In situ observations made extremely close to the Sun, by PSP, have been matched against remote sensing observations of the corona itself to reveal how reconnection structures and accelerates the fast solar wind.

Instances of reconnection, in different solar system contexts, reveal a universal process but leave unanswered some of the most elementary questions about its operation. It is not known, for instance, what controls the onset of magnetic reconnection. Is it triggered by global forcing or by instabilities inside the local current sheets? It is also not understood why reconnection appears to be bursty and patchy in very different regions (see Figure 2-14), while often quasi-steady state and spatially extended in others. How does a process active on the smallest scales affect those operating at the largest scales? To answer these critical questions requires the determination of the spatial scale size and evolution of the reconnection region, as well as the simultaneous knowledge of microscale properties at the reconnection site and its surrounding large-scale dynamics. A major goal for the next decade is to achieve universal understanding of when and where reconnection can occur and to predict the occurrence and consequences of this process for different astrophysical and Earth-laboratory contexts.

Cross-Scale Coupling Through Interactions Between Magnetic Reconnection, Turbulence, Shocks, Wave–Particle Interactions, and Particle Acceleration

Although reconnection, turbulence, and shocks have been studied independently for decades, theory and observations made in the past 10 years have pointed to the exciting possibility that the distinct phenomena are

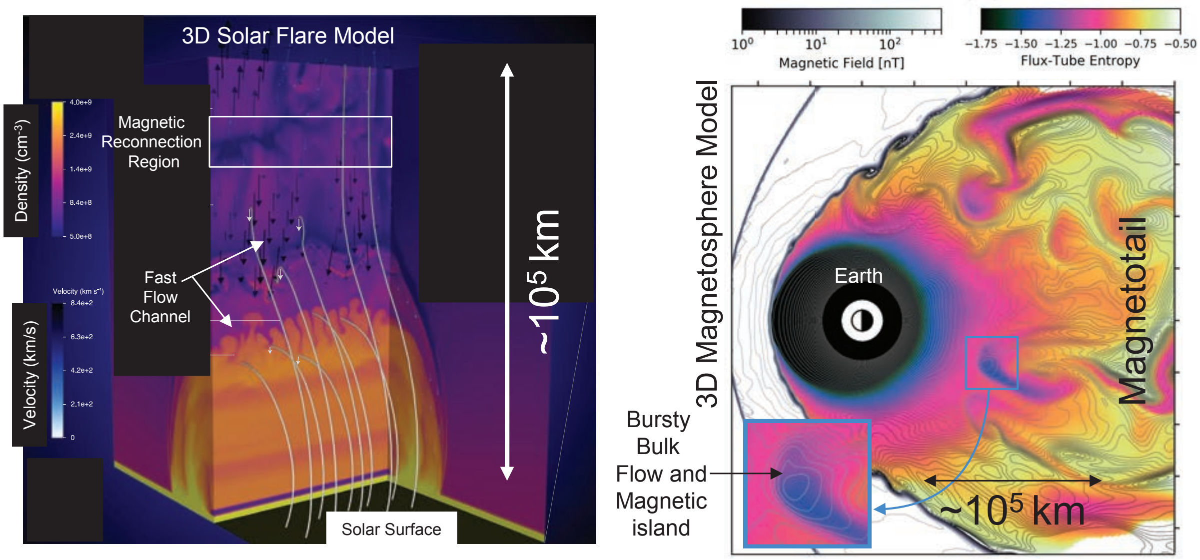


FIGURE 2-14 Bursty and patchy manifestations of magnetic energy release in two different regions of the heliosphere, driven by different explosive phenomena: (*Left*) supra-arcade downflows above a solar flare release energy by moving downward and (*Right*) bursty bulk flows in Earth's magnetosphere are created by magnetic reconnection in the magnetotail and are driven earthward and release energy.
SOURCES: C. Shen, B. Chen, K.K. Reeves, et al., 2022, "The Origin of Underdense Plasma Downflows Associated with Magnetic Reconnection in Solar Flares," *Nature Astronomy* 6:317–324, https://doi.org/10.1038/s41550-021-01570-2, reproduced with permission from SNCSC; Adapted from Sorathia et al. (2021), https://doi.org/10.3389/fspas.2021.761875. CC BY 4.0.

intimately related. Earth's bow shock serves as an ideal structure to study the inter-relationship between these processes. Quasi-parallel shocks have been observed to generate large numbers of turbulent current sheets, many of which are reconnecting within the shock transition itself. A major surprise was the discovery that the small-scale reconnection often involves only electrons, with no ion coupling. The turbulence convects downstream, where reconnection continues to operate.

Turbulence is generated during the reconnection process throughout the reconnection layer. This turbulence could accelerate charged particles to high energies, possibly explaining how reconnection accelerates electrons and ions in many phenomena including solar flares. What is not clear is how much of the energy released through reconnection appears as turbulence. An open question is whether reconnection plays a significant role in the global dissipation of energy in shocks and turbulence. Answering this question requires simultaneous measurements, with proper instrumentation, of shocks and the surrounding turbulence and current sheets, from kinetic to MHD scales. The HelioSwarm mission (currently in development) promises to reveal this process at work in the heliosphere, and MUSE (also in development) will do so in the flaring corona. The future findings by HelioSwarm and others to be envisaged in the upcoming decade will have the potential of bringing all major fields of plasma physics together.

Shock research has seen tremendous progress in the past decade thanks to unprecedented high resolution in situ measurements at Earth's bow shock and interplanetary shocks. The energy conversion mechanisms at shocks have been directly measured, including such mechanisms as a cross-shock electrostatic potential, current-driven instabilities, magnetic reconnection in the shock transition region, other wave-particle interactions, and particle acceleration and reflection. The region in front of the bow shock (the foreshock) is often turbulent, and this turbulence likely plays an important role in the fate of plasma as it crosses the shock (Figure 2-15). However, a global characterization of the bow shock, the heating and partition of energy across the shock, and the resulting turbulence has not been achieved due in part to the lack of multiscale measurements of the shocks and their surrounding regions. The termination shock at the edge of the solar system may play some role in the production and modulation of anomalous cosmic rays, although the nature of that role remains to be established.

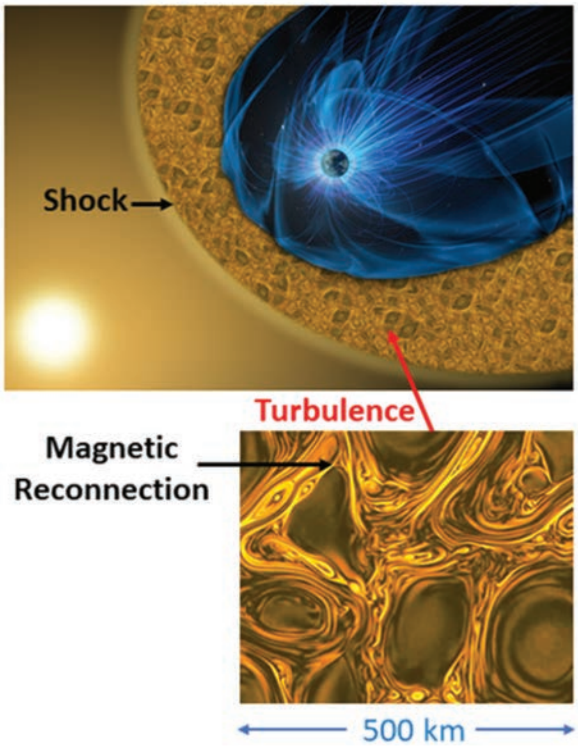


FIGURE 2-15 Magnetospheric Multiscale mission discovery of the interplay among shocks, turbulence, magnetic reconnection, and particle energization around Earth's bow shock. Understanding their global impacts requires simultaneous measurements of shocks and the surrounding turbulence and current sheets across multiple scales, potentially bringing all major fields of plasma physics together.
SOURCES: NASA Goddard's Conceptual Image Lab/Lisa Poje; NASA Goddard/Mary Pat Hrybyk-Keith; NASA Goddard's Conceptual Image Lab/Josh Masters.

Instabilities and Waves with Cross-Scale Consequences

Wave–particle interactions lead to some of the most energetic phenomena in near-Earth space, such as particle acceleration in the radiation belt, the acceleration of particles that create the aurora, and the acceleration of ionospheric ions to create ion outflows. The Van Allen Probes made significant advances in the understanding of the dynamics of the inner magnetosphere, including the radiation belts and ring current, showing definitively that local acceleration by wave particle interactions occurs in the center of the radiation belts and are responsible for the formation, acceleration, and loss of energetic particle populations.

Combined data from Van Allen Probes, CubeSats, and balloons, together with modeling, revealed that orders-of-magnitude depletions of the radiation belts can occur in a few hours or less, caused by a combination of magnetopause shadowing and precipitation into the atmosphere owing to interactions with plasma waves. These results revealed the importance of nonlinear wave-particle interactions, drift-orbit bifurcations, and field-line-curvature scattering mechanisms in the radiation belts.

Open questions remain as to how wave particle interactions drive strong auroral outflow in both the dayside cusp and the nightside aurora. The outflowing particles are transported to the magnetosphere and could significantly impact magnetospheric dynamics during geomagnetically active times. Similarly, wave particle interactions are believed to accelerate particles to high energies to create the aurora, but exactly where and how electromagnetic energy is converted to particle energy to power the aurora is still unknown.

In the ITM system, key state parameters of the upper-atmosphere ITM system exhibit structure over spatial and temporal scales that span many orders of magnitude, from kinetic effects of individual particles to global-scale oscillations. Many critical ITM processes are mediated by their bidirectional feedback coupling across these scales, often involving atmospheric waves. One example of a two-way, cross-scale coupling process is the coupling of small-scale atmospheric gravity waves with the large-scale wind flow. The wave dissipation is strongly influenced by the background flow. Meanwhile, gravity waves modify the flow (generating regions of strong wind shear), and when they dissipate, they in turn modify the background flow. Much of the energy and momentum from the lower atmosphere waves is deposited in the upper boundary of the atmosphere (lower thermosphere and ionosphere), influencing the mean state of the system. The altitude, location, and timing of this transition is still unknown, as well as the processes and scales that govern it. The Atmospheric Waves Experiment and ground-based observations, along with the DYNAMIC mission, offer the opportunities to elucidate the mechanisms that govern the transition in chemical, dynamical, and thermal drivers across the ITM from ~100–200 km; determine how the gravity wave spectrum cascades throughout the thermosphere and impacts the ITM system; and determine how nonlinear coupling between mean neutral atmosphere circulation, tides, and planetary waves drives ITM variability.

There is also significant cross-scale coupling associated with ionospheric plasma motion and instabilities. The ionosphere exhibits a high degree of spatial and temporal variability resulting from a wide range of drivers. These drivers include geomagnetic activity and electrodynamic effects of atmospheric waves, which generate features ranging from small-scale instabilities to global circulation patterns. At high latitudes, the auroral convection pattern has mesoscale variability embedded within a synoptic pattern, cascading into small-scale instabilities. Kelvin-Helmholtz instabilities are generated by, and subsequently regulate, large-scale and mesoscale flow shears. At equatorial latitudes, Rayleigh-Taylor plasma instabilities result in the formation of equatorial plasma bubbles (Figure 2-16) that are deleterious to the Global Navigation Satellite System (GNSS) and radio signal propagation. The quasi-periodic spacing of these features seen by GOLD may be indicative of an atmospheric wave, but what role such waves play in determining these structures is not known. Variability of these drivers on their various scales is poorly characterized owing to sparse data sets and inadequately characterized model drivers, precluding assessment of the role of preconditioning on these drivers and observed mesoscale variability.

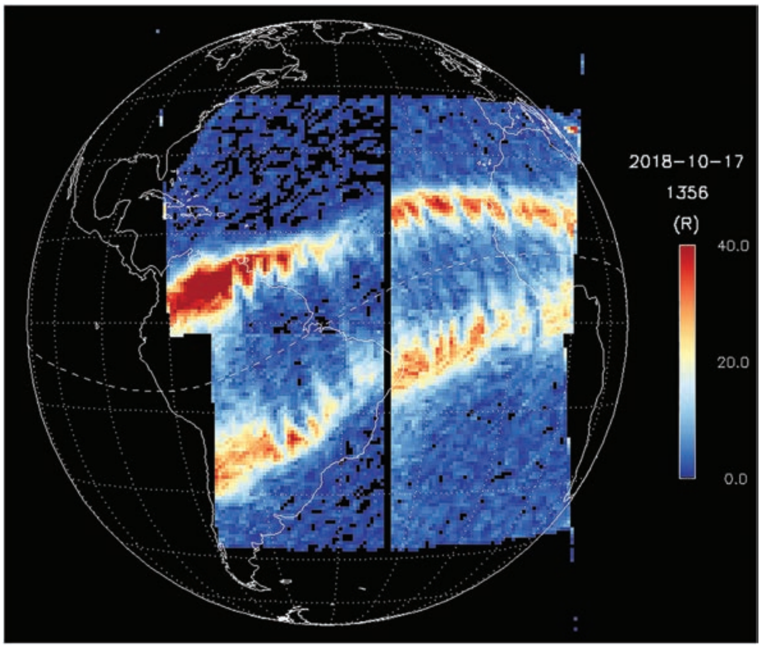


FIGURE 2-16 Plasma bubbles observed by the GOLD (Global-scale Observations of the Limb and Disk) mission. These bubbles may indicate atmospheric waves and the role of these waves in the formation of these bubbles is the subject of research in the next decade.
SOURCE: Eastes et al. (2019), https://doi.org/10.1029/2019GL084199. CC BY 4.0.

GDC and DYNAMIC together will explore elements of system-level quantification to address the following priority science goals: determining how plasma irregularities are driven by and regulate large-scale ITM phenomena, and quantifying the relative roles of preconditioning and seeding mechanisms in controlling the emergence and evolution of ionospheric irregularities. Critically, GDC will exploit the phased deployment of its constellation to allow the investigation of different scales of drivers and the ITM response to solar and magnetospheric energy inputs. EZIE will investigate current closure at small scales, instantaneously, addressing cross-scale coupling phenomena on a restricted regional scale. Enhanced ground-based observations can provide the capability to determine how small-scale structuring in high-latitude ITM state parameters leads to mesoscale conductivity enhancements, which have aggregate global significance.

Nature and Consequences of Coupling Between Ionized and Neutral Fluids

Ionized plasmas and neutral fluids typically behave in different characteristic fashions, responding as they do to different kinds of forces. In several key locations in the solar system, they coexist and interact with one another to produce surprising behavior we are only beginning to understand.

Electric currents and large-scale electric fields are driven in Earth's high-latitude upper atmosphere by neutral winds and electric potentials of magnetospheric origin. At low and equatorial latitudes, polarization electric fields created by the E- and F-region neutral wind dynamos effectively cause the uplift of the F-region plasma, creating the equatorial ionospheric anomaly.

Effective identification and quantification of plasma neutral coupling across scales has been hindered mainly by the narrow science focus of past and current missions that consider competing drivers and physical processes mainly in isolation from one another. The physical mechanism that governs the initiation, growth, and suppression of equatorial plasma bubbles is not well understood, and potential "seeding" of bubbles by gravity waves, especially during geomagnetically quiet periods, is still debated. The neutral wind field exhibits significant temporal variability on hour-to-day timescales, constituting upper-atmospheric "weather" during even the quietest geomagnetic conditions. While the theory that supports data analysis and numerical modeling is well established, quantitative knowledge regarding the numerous driver/response relationships and their relative significance under different conditions (spatial, climatological, temporal) is under-constrained.

The interaction of the plasma in the inner magnetosphere with the neutral exosphere, the outermost layer of Earth's atmosphere, is one of the most critical processes leading to the ultimate loss of the plasma energy via charge exchange. The exosphere is constantly changing in response to disturbances in space above it and to the atmosphere below. However, it is still not known what the size, shape, and density profile of the exosphere is and how these parameters change with time. The NASA Carruthers Geocorona Observatory seeks to answer these basic questions.

The termination shock and heliopause are also influenced by the coupling of neutral and ionized components as neutrals entering the solar system are picked up by the out-bound solar wind. This interaction has been the subject of extensive modeling but has been observed chiefly with remote sensing through energetic neutral atoms by IBEX and soon with IMAP. These remote observations leave unclear details in the interaction between neutral and ionized components in this, the most remote corner of the local cosmos. Until these are clarified, the full nature of the solar system's outer boundary will remain a puzzle.

In the past decade, the importance of plasma-neutral coupling in the layer separating the solar interior from its hot corona has been recognized. Persistent puzzles concerning the emergence of dynamo-generated magnetic fields into the corona may be solved, or mitigated, by considering this coupling. Explaining the observed thermal structure of the chromosphere may require invoking the interaction between its ionized and neutral components. While these effects have now been identified, verifying and exploring their significance is a task for the next decade. Inouye and EUVST will make important contributions to the puzzle.

2.2.4 A Laboratory in Space: Building Blocks of Understanding—Theme 2 Synopsis

Table 2-2 summarizes the guiding questions, focus areas, and observations for Theme 2. The space around the planets and the Sun hosts myriad physical processes, many of which remain poorly understood. These fundamental processes are the focus of Theme 2 and give rise to some of the most spectacular and intriguing phenomena in

TABLE 2-2 A Laboratory in Space: Building Blocks of Understanding—Theme 2 Guiding Questions, Research Focus Areas, and Observations Needed to Carry Out the Research

Guiding Question	Focus Areas	Observation Needs	Model Needs
How is the Sun's global magnetic field created and maintained, and what causes its cyclical variations?	• Flows and fields across all solar latitudes • Linkage of the interior field to the global heliosphere • Longitudinal variation of the dynamo and the field	*Sun:* Remote sensing measurement of flows and magnetic field at one of the Sun's polar regions and from one or more vantage points off the Sun–Earth line. Imaging of the corona from a wide range of longitudes, either from multiple vantage points around the ecliptic or from a polar vantage point.	Global models of the magnetic field generation that also incorporate emergence through the solar surface and creation of a corona. Integrated, physics-based model of the corona and solar wind.
How do fundamental processes create and dissipate explosive phenomena across the heliosphere?	• Energy conversion in explosive events • Consequences of the aggregation of individual explosive events • Response of systems to explosive events	*Sun:* High cadence spectroscopic imaging of solar flares. Coronal and chromospheric vector magnetic field measurements. *Magnetosphere:* High-resolution distributed multipoint in situ and remote-imaging measurements of the critical transition regions in the magnetotail, the dayside magnetopause, and the ionosphere/cusp regions to capture the large-scale dynamics of explosive magnetospheric phenomena and their global effects on the ionosphere. *Ionosphere–thermosphere–mesosphere (ITM):* Constellation measurements of the global ITM and middle atmosphere key parameters in high spatial and temporal cadence. Ground-based observations of volcanic events, and high latitude magnetospheric and solar wind energy deposition.	Models spanning local scales, where explosive events are triggered and nonideal and/or kinetic effects are manifest, through global scales, where the effects of these events aggregate into a system-level response.
How do fundamental processes govern coupling across spatial scales?	• Cross-scale implications of magnetic reconnection • Cross-scale coupling through interactions between magnetic reconnection, turbulence, shocks, wave-particle interactions, and particle acceleration • Instabilities and waves with cross-scale consequences • Nature and consequences of coupling between ionized and neutral fluids	*Sun:* Measurements of the reconnecting magnetic field in solar eruptive events. *Heliosphere:* Measurement of pick-up ions across the termination shock and heliosheath. *Magnetosphere:* Simultaneous, multiscale measurements of shocks and the surrounding turbulence and current sheets. Measurements of waves and particles, and simultaneous imaging at multiple altitudes between the ionosphere and magnetosphere. *ITM:* Concurrent and coincident observations of ITM forcing from above and below, and global key ITM parameters at a range of temporal and spatial scales using a constellation of satellites with varying separation, coupled with a network of ground-based observations, spanning from the lower to upper thermosphere.	Models covering spatiotemporal scales from energy injection through micro-scales where energy is dissipated. Conversely, models of micro- and meso-scale processes that extend to scales large enough to capture global system impacts.

the solar system. Progress on this theme relies on missions, projects, and theory and modeling that use the local cosmos as a laboratory.

2.3 THEME 3—NEW ENVIRONMENTS: EXPLORING OUR COSMIC NEIGHBORHOOD AND BEYOND

2.3.1 Exploring New Environments

Exploration is driven by humanity's fundamental curiosity about the world. Solar and space scientists have always been intrepid explorers, pushing the boundaries of human understanding in space with the first detailed solar observations, the first in situ measurements in space by Explorer I, and the first observations streaming back from the very edge of the solar system and beyond by the Voyager spacecraft. In this dawn of a new age of multipoint measurements, systems science, and unprecedented access to space, solar and space physicists are looking outside the traditional domain of the field to new questions and curiosities in the local cosmic neighborhood and beyond.

There are new environments to explore, as well as new technologies and approaches to bring to previously studied regions. The core focus of solar and space physics is and remains the Sun, its plasma and magnetic fields, its interactions with planetary and small body magnetospheres and atmospheres, and the basic physics of space plasmas. Earth–Sun interactions continue to be a major focus because geospace is the realm in which human activity is centered. Yet, there is an unwritten chapter of discovery, and much to be learned from the magnetospheres and atmospheres of other planets. Discoveries in other environments provide new insights into Earth's interaction with the space environment. As for the Sun itself, little is known about the solar poles, a region ripe for exploration. Moving outward, the boundary of the solar system where the Sun's influence wanes and is replaced by the interstellar environment, there is much to be discovered. Knowledge of these borderlands is critical to understanding other stellar astrospheres. In particular, plasma processes happening on exoplanets and the evolution of young stellar winds play important roles in the environments of other stellar systems.

There are new discoveries to be made even within regions that have been studied for years in solar and space physics, owing to novel methods of accessing them and new approaches that emphasize a systems viewpoint (see Theme 1). Earth's own upper atmosphere is one of those regions. The ionosphere–thermosphere system has been understudied for decades. While it is often a target of suborbital sounding rocket missions, the ability to make more continuous in situ observations is limited below ~300 km in altitude. With the advent of CubeSats or microsats that enable shorter spacecraft lifetimes experienced at low altitudes, and advances in fuel technologies that allow for periodic dips into this region, this system is ripe for discovery. Extending downward in the atmosphere, the mesosphere and upper stratosphere are sinks for energetic particle precipitation from space, yet so far, these have not been studied with the attention they merit. Similar opportunities exist to answer fundamental questions about the connections between space and climate. Enhanced collaborations across a range of Earth and geoscience disciplines enables pursuit of these answers. The anticipated return of humans to the Moon in the next decade is opening new doors to investigate space plasma processes and solar wind-lunar interactions. There is much to be learned about other moons and small bodies embedded in the continuous and ever-changing solar wind.

2.3.2 History of Exploration in Solar and Space Physics

Paleolithic rock drawings are the earliest evidence that humans have observed the Sun, its motion in the sky, seasonal changes, and the Sun's influence on Earth. Observations of sunspots were reported in China before 800 BCE. The invention of radio communication quickly revealed (in the early 1900s) the ionospheric layer in Earth's upper atmosphere. Cosmic rays were discovered by Victor Hess in 1912 with balloon experiments. The first detection of a magnetosphere came with discovery of bursts of radio emission from Jupiter in 1954 that revealed energetic electrons are trapped in the planet's strong magnetic field (Burke and Franklin 1955). This was followed in 1958 by the launch of the first U.S. satellite, Explorer 1, and James Van Allen's discovery of Earth's radiation belts that now carry his name. The explosion of space exploration that followed revealed the roles of particles and fields in space. For example, direct detection of the solar wind provided new insights into the Sun's influence on the solar system and Earth. The Mariner missions flew past Mars and Venus in the 1960s, revealing atmospheres, ionospheres (but not internal magnetic fields), and solar interactions. The Apollo missions uncovered the Moon's exposure to the solar wind and the potential risks of particle radiation to astronauts. (Luckily, the Apollo astronauts missed the big storms.) In the early 1970s, Pioneer 10 and 11 passed through the magnetosphere of Jupiter confirming the presence of intense fluxes of trapped energetic particles and began a new era of outer heliosphere exploration. This era continues today with the two Voyager spacecraft, now nearly 50 years in space, and New Horizons, now more than 18 years in space. The Voyager spacecraft have provided the first delimitative measure of the extent of the heliosphere.

Over the past 65 years, exploration of the space environment has evolved from single spacecraft making sparse measurements with limited instrumentation to highly capable, multicomponent, multispacecraft missions that coordinate multiple types of measurements, and collaboration between both space- and ground-based facilities. Such measurements have revealed the physical processes that link activity on the surface of the Sun to variations in the solar wind that drive Earth's space environment and impact all planetary objects and beyond, out into the interstellar medium.

The guiding questions and research focus areas for Theme 3 (Figure 2-17) are intrinsically interdisciplinary in nature. They cross discipline boundaries that have traditionally separated solar and space physics from

FIGURE 2-17 Guiding questions and research focus areas within Theme 3—New Environments: Exploring Our Cosmic Neighborhood and Beyond, exploring the space physics environments beyond the Sun–Earth connections—to other planetary and stellar systems.
SOURCE: Created by AJ Galaviz III, Southwest Research Institute.

planetary science, astronomy and astrophysics, and Earth sciences. Comparing Earth's magnetosphere and ionosphere to those of other planets, the Sun and heliosphere to other stars and astrospheres, and understanding how this system is conducive to life, helps answer the boldest questions about the solar system and potential habitability of other systems. In this sense, solar and space physics builds a new connection between these disciplines. Answering these guiding questions requires cross-discipline, cross-divisional, and cross-directorate collaboration. This section is partially a call for action to embolden the agencies to imagine ways in which the traditionally distinct fields can partner with each other to make transformational scientific progress on these ambitious questions.

2.3.3 Guiding Question: What Can We Learn from Comparative Studies of Planetary Systems?

Mass and Energy Flow Processes Driving Planetary Magnetospheres

A major focus of this report is how Earth's magnetosphere and ionosphere respond as a system to the solar wind and interplanetary magnetic field. Exploration of the magnetospheres of other planets has shown that a similar system-wide response occurs; however, there are significant variations in this response (e.g., with distance from the Sun, strength and/or orientation of the magnetic field, and different plasma regimes). Furthermore, there are clearly different drivers in these other systems (e.g., rotation and satellite sources).

In the past decade, there have been particles and fields measurements made with instruments on planetary missions (funded by NASA Science Mission Directorate's Planetary Science Division) that have provided new insights into magnetospheric science. For example, in 2011, MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging) started its 4-year mission orbiting Mercury, exploring how vigorous solar wind at ~0.4 AU, and an Earth-like reconnection-driven Dungey cycle drive violent storms in Mercury's small magnetosphere (Figure 2-18). The Dungey cycle loading and unloading of the magnetic flux in the tail lobes of Mercury is much more intense than at Earth and takes place on timescales of several minutes and closely resembles the several-hour long magnetospheric substorms observed at Earth. Electrons accelerated by tail reconnection precipitate onto Mercury's surface, just equatorward of the polar cap boundary, and stimulate X-ray fluorescence, Mercury's analogue to Earth's auroral ovals.

At the opposite end of the size scale is Jupiter's magnetosphere (Figure 2-18); Pioneer and Voyager flybys in the 1970s showed it to be ~100 times bigger than Earth's. This huge size is owing to the combination of a very strong internal magnetic field, a weaker solar wind at ~5 AU, and a prodigious 1 ton/s source of material from the volcanic moon Io. The Galileo mission made 34 orbits around Jupiter and revealed that the moon Ganymede has its own magnetic field (comparable in strength to that of Mercury), making a magnetosphere within a magnetosphere, albeit surrounded by subsonic plasma flow (unlike the supersonic solar wind). Galileo also revealed induction currents at Europa, proving the existence of a liquid ocean under the icy crust. This discovery has made Europa a major target for exploring habitability and searching for life. Currently the Juno mission has been in a polar orbit around Jupiter for 8 years (with hope for another year or two before the particle radiation is too damaging), observing Jupiter's intense aurora and measuring the associated particles and fields. Before Juno, the natural tendency was to invoke similar auroral processes to those at Earth. However, Juno measurements are showing a highly dynamic system, with turbulence playing a much stronger role than at Earth.

Meanwhile, in 2017, the Cassini spacecraft completed its mission after orbiting Saturn for 13 years. Again, an active satellite—Enceladus in this case, with active plumes of water—is the major source of plasma (made of dissociated and ionized water products). Cassini explored how magnetospheric plasma interacts with moons (including Titan) and rings, plus how ionosphere–magnetosphere coupling drives a strong aurora. A major mystery of Saturn's magnetosphere is the high level of symmetry of the dynamo around the planet's spin axis, combined with the noticeable oscillation produced by ionosphere–magnetosphere coupling.

In dramatic contrast to Saturn's tightly aligned magnetic field, the magnetic fields of Uranus and Neptune are tilted at large angles (~50°) from their spin axes and are highly irregular (nondipolar). The Voyager flybys (1986 and 1989) provided a glimpse of these weird magnetospheres and once again showed the range of variability in planetary magnetospheres. It is particularly intriguing how the magnetosphere of Uranus changes with season because

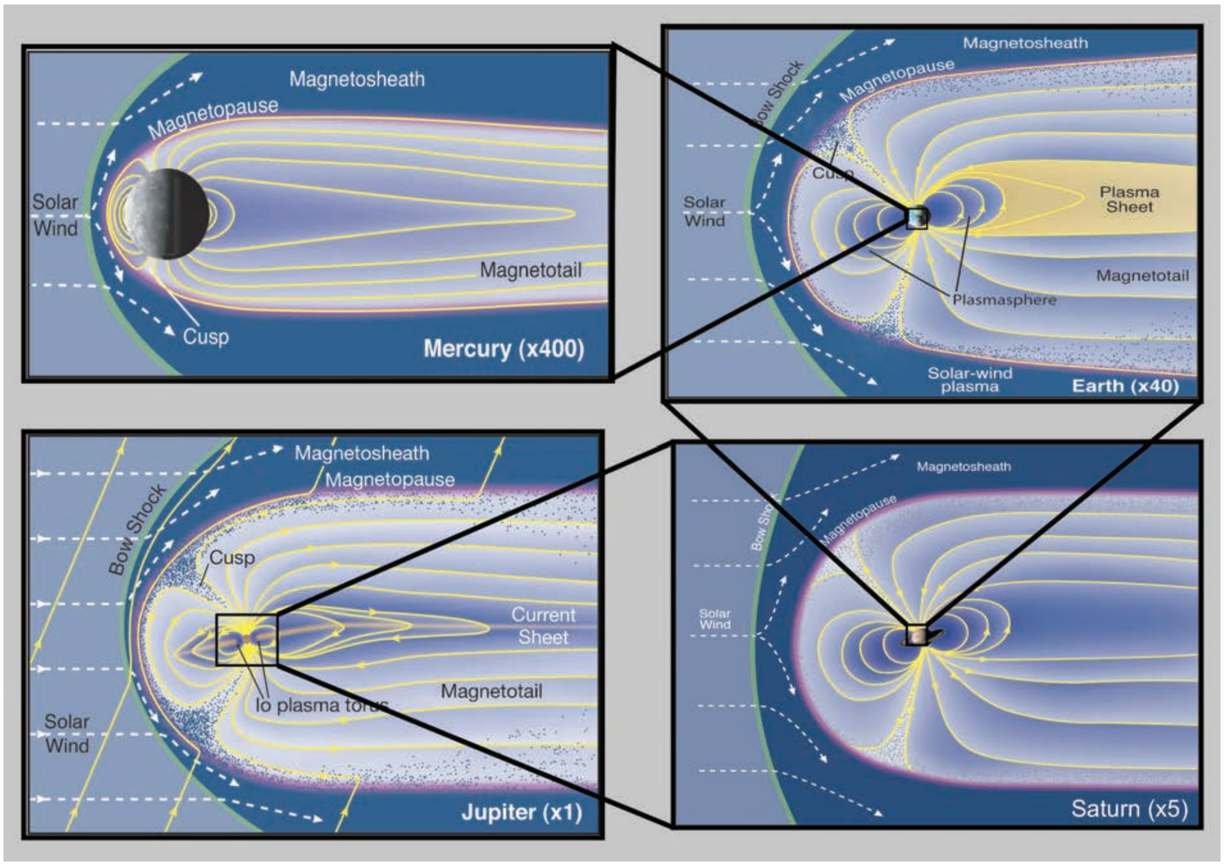


FIGURE 2-18 There is a factor of 400 in the absolute scales of planetary magnetospheres ranging from Mercury to Jupiter. The huge differences in scales are evidence for different external and internal drivers of these magnetospheres. The differences and similarities of these magnetospheres provide guidance for understanding exoplanet magnetospheres.
SOURCE: Bagenal and Bartlett (2024).

Uranus's spin axis is close to the ecliptic plane (obliquity = 98 degrees). This extreme tilt leads to radical changes in the geometry of the solar wind and interplanetary magnetic field interacting with Uranus's magnetosphere. Figure 2-19 shows how the combination of the high obliquity of Uranus's spin axis and high tilt of the magnetic field means that the magnetosphere of Uranus varies significantly over both the ~17-hour rotation period as well as the 84-year orbital period. As Uranus is the closest representative of an ice giant planet, understanding how this magnetosphere differs from that of Jupiter and Saturn is important for modeling of exo-ice giants around other stars.

Future Missions

ESA (with NASA collaborations) already has missions on their way to planetary targets—BepiColombo to Mercury and Jupiter Icy Moons Explorer (JUICE) to Jupiter—carrying instruments that make particle and field measurements relevant for solar and space physics. In the 2030s, JUICE is scheduled to encounter Jupiter and eventually go into orbit around Ganymede to explore this moon's intriguing magnetosphere. NASA's Europa Clipper will be launched in 2024 and the faster cruise phase of the mission leads to similar arrival times with JUICE, allowing synergistic measurements between JUICE and Europa Clipper. To optimize the scientific return from these missions, it is key that support is provided for an interdisciplinary approach to operations, data processing, and modeling at these planetary targets.

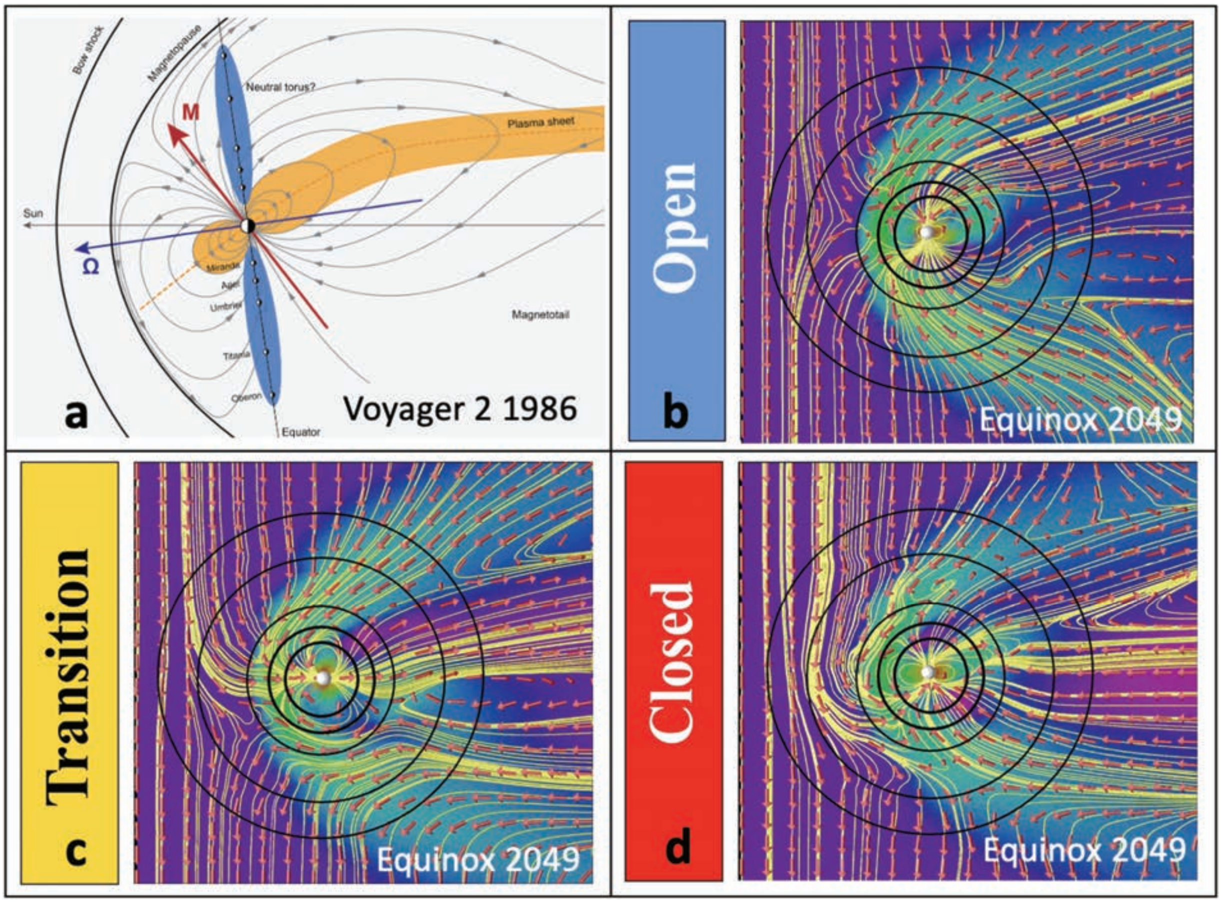


FIGURE 2-19 Magnetosphere of Uranus at different seasons and phases. The Sun is to the left. The satellite orbits (black) are perpendicular to Uranus's spin axis. Top left (a) the configuration at the time of the Voyager 2 flyby in 1986, close to solstice. The other diagrams are from an magnetohydrodynamic model centered on equinox in 2049 and illustrate the dynamic nature of the magnetosphere over the ~17-hour rotation period. The global configuration of the magnetosphere is open, in transition from open or closed, or closed to the solar wind. The colored shading illustrates the modeled plasma pressure, while the yellow lines and red arrows show the magnetic field lines and directions respectively. This model configuration is for a fixed vertical interplanetary magnetic field (IMF). The variable IMF further contributes to magnetosphere dynamics.
SOURCES: (a) Adapted and reprinted from C.S. Arridge, N. Achilleos, J. Agarwal, et al., 2014, "The Science Case for an Orbital Mission to Uranus: Exploring the Origins and Evolution of Ice Giant Planets," *Planetary and Space Science* 104(A):122–140, Copyright (2014), with permission from Elsevier; (b, c, and d) From Cao and Paty (2017).

The planetary science decadal survey *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023a) identifies the Uranus Orbiter and Probe (UOP) as the highest-priority new flagship mission for initiation in the decade 2023–2032. The report states "UOP science objectives address Uranus's (1) origin, interior, and atmosphere; (2) magnetosphere; and (3) satellites and rings. UOP will provide ground truth relevant to the most abundant, similarly sized class of exoplanets." From a space science perspective, it is key that such a mission carry sufficient particles and fields instrumentation to fully explore the unique magnetosphere of Uranus.

Interactions of Plasmas with Atmospheres and Solid Body Surfaces

Until recently, the majority of the space science community embraced the idea that an intrinsic magnetic field was required to shield a planet from the solar wind eroding its atmosphere. While a planetary magnetic field does

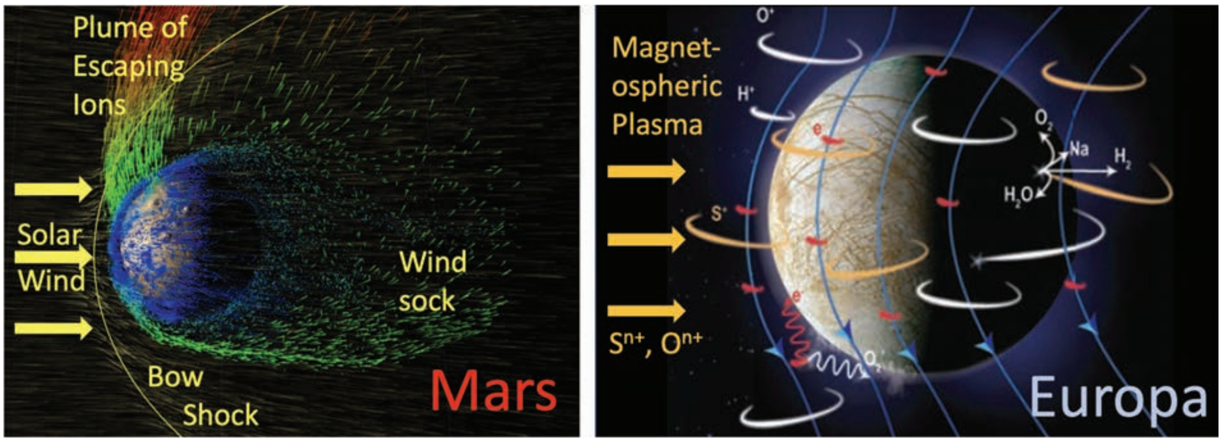


FIGURE 2-20 Plasma interactions with planetary atmospheres depend on the incoming plasma properties as well as the density, thickness, and composition of the atmosphere. These interactions produce a complex and variable outflow from the planet or moon. Ultimately, this outflow has implications on the long-term viability of planetary atmospheres.
SOURCES: (*Left*) NASA's Scientific Visualization Studio and the MAVEN Science Team; (*Right*) Johns Hopkins APL/Joe Westlake.

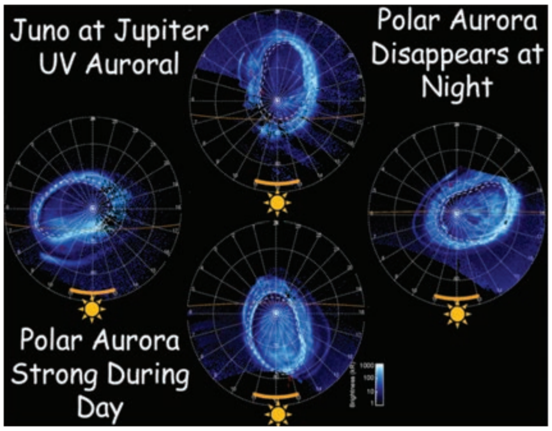
protect the atmosphere from direct solar wind impact (causing sputtering and ionization), a magnetosphere can also enhance the net escape rate via the polar cap and cusp. In fact, there is no consensus on what fraction of outflowing ions ultimately escape Earth's magnetosphere. Furthermore, when the solar wind impinges on an unmagnetized planet with a significant ionosphere, the interplanetary magnetic field piles up on the dayside of the planet, deflects the solar wind around it, and forms a magnetotail downstream. This shielding effect of the induced magnetosphere is potentially on par with that provided by an intrinsic magnetic field. Contrary to what was previously believed, the absence of a strong planetary magnetic field does not necessarily lead to atmospheric loss—and, conversely, a strong magnetic field does not necessarily shield the atmosphere from escape.

This issue of atmospheric escape at induced magnetospheres has been explored with direct measurements at Venus (by Venus Express and PSP), Mars (by Mars Atmosphere and Volatile EvolutioN [MAVEN]) (see Figure 2-20), as well as at Pluto (with New Horizons). Furthermore, plasma interactions with atmospheres have been studied at outer planet moons that have significant atmospheres and are embedded in their large planetary magnetospheres—for example, Titan and Enceladus at Saturn and Io, Europa, and Ganymede (where further complexity is added via the moon's own magnetic field; see Figure 2-20) at Jupiter.

For objects that do not have significant atmospheres (i.e., Earth's Moon, asteroids, Kuiper Belt objects, and the majority of the many moons of the giant planets), solar radiation (including X-rays and UV), the solar wind, and energetic particles (energetic solar protons and galactic cosmic rays) directly bombard the surface. The net effect depends on the energy and flux of the bombarding particles as well as the composition of the surface material. As a result, the chemistry and structure of the surface materials can be altered over time and sputtering of material forms a tenuous atmosphere or escapes into space.

Future Missions

At Jupiter, Juno made observations on flybys of Ganymede, Europa, and Io and will make several more (distant) flybys of Io before the end of the mission. Toward the end of the next decade, JUICE and Europa Clipper will focus on Ganymede and Europa respectively. Escape and Plasma Acceleration and Dynamics Explorers (ESCAPADE) is a heliophysics mission with multiple small satellites that will study the solar wind interaction with the Martian atmosphere. In the longer term, there are planned Venus orbiters, the Uranus Orbiter Probe mission (likely including satellite flybys), and multiple missions to the Moon. These missions need to be equipped with appropriate particles and fields instrumentation. Making the most of these exciting new data sets requires funding for interdisciplinary data analysis and modeling studies.



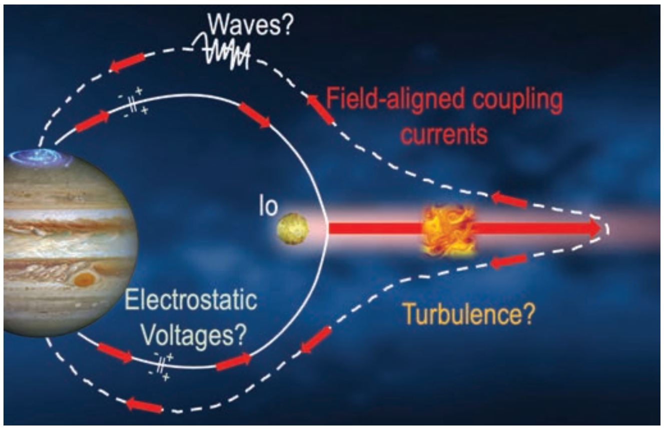


FIGURE 2-21 NASA's Juno mission has been revealing Jupiter's aurora. These observations show distinctive features that are very different from Earth's aurora.
SOURCES: (*Left*) Greathouse et al. (2021); (*Right*) Bagenal (2024).

Diversity of Auroral Processes

Fundamentally, aurora are emissions produced when particles hit an atmosphere. Auroral emissions have been observed at Earth, Jupiter, and Saturn, as well as sparsely at Uranus and Neptune. Recently, auroral emissions have been also observed at Mars. While there are some similarities in the physical processes that produce aurora, the situation at each planet is different. For example, Earth's auroras are driven by the solar wind interaction with the magnetosphere and are associated with ITM coupling in the polar regions. At Jupiter and Saturn, the primary driver is the coupling of the magneto-disk to the rotation of the planet, also via ITM coupling. The local processes that accelerate the particles bombarding the atmosphere at Earth and Jupiter are similar—quasi-static, field-aligned electric potentials and wave-driven turbulent (broadband) heating—but the former process dominates at Earth while the latter dominates at Jupiter (Figure 2-21). Moreover, the power emitted at Jupiter is 100 times that at Earth. Juno is also showing at least two types of unusual aurora in the polar region, poleward of the main auroral emission. Earth-orbiting X-ray telescopes (e.g., Chandra, XMM) have observed X-ray auroras from Jupiter for decades. These X-rays have a spectrum that suggests they were created by acceleration of heavy ions to megaelectronvolt energies and stripped of several electrons. Juno is now directly measuring these megaelectronvolt ions that are constantly bombarding the polar region. Yet there is little understanding of how megavolt potentials are produced along Jupiter's magnetic field to accelerate these aurora-exciting ions. Another somewhat uniform region of emission near the poles (called the swirl when first detected with the Hubble Space Telescope) disappears when the auroral region rotates onto the nightside of Jupiter. The ITM processes that control this local time effect are unknown.

Over the past decade, it has become clear that solar wind interaction with Mars also produces auroral emissions. The MAVEN Imaging Ultraviolet Spectrograph instrument has mapped out hydrogen Lyman-α and Lyman-β emissions on the day- and nightsides of Mars, respectively (Figure 2-22). The nightside emission is thought to be produced by precipitation of energetic solar protons. The dayside emission is related to solar wind protons bombarding the dayside atmosphere. More recently the United Arab Emirates' Mars Mission (EMM) ultraviolet spectrometer instrument detected far UV oxygen emissions on the dayside of Mars with detailed structures that suggest solar wind thermal electrons penetrate through the upper atmosphere but are directed by the strong crustal (remnant) magnetic fields to the footprints of the field lines. Predictions indicate that the aurora of Mars would be readily observed at visible wavelengths (the same oxygen lines that are visible on Earth), and camera systems as simple as modern smartphones should be capable of recording dynamic auroral displays anywhere on the surface of Mars, similar to observations of the polar aurora at Earth.

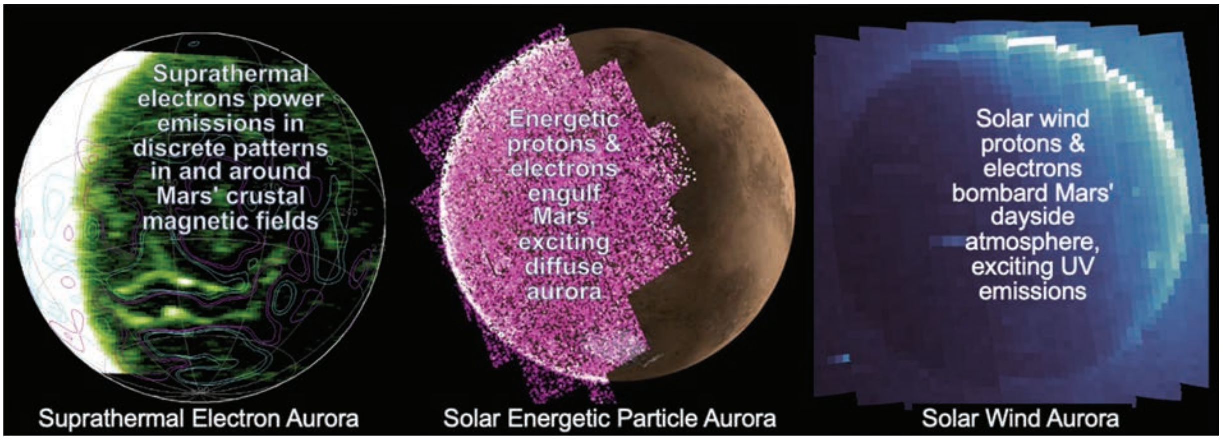


FIGURE 2-22 Auroral emissions at Mars have different source mechanisms, reflecting the complex interaction of the space environment with the planet's atmosphere and crustal magnetic fields. Left: Oxygen emission in the far ultraviolet (FUV) observed by the EMM/EMUS instrument. Middle, hydrogen Lyman-β, Right: Lyman-α emissions observed by MAVEN/IUVS instrument.
SOURCES: (*Left*) Lillis et al. (2022), https://doi.org/10.1029/2022GL099820. CC BY-NC-ND 4.0; (*Middle and Right*) Adapted from Schneider et al. (2021).

Future Studies

Recent planetary missions (Juno, Cassini, MAVEN, and EMM) have revealed the diverse auroral processes that occur at Jupiter, Saturn, and Mars. The next steps require considerable interdisciplinary (e.g., combining atmospheric and space physics) modeling of the processes, their comparison with the multitude of results from Earth's auroral processes, and better understanding of the auroral processes at Earth. The UOP mission will use its auroral instrumentation to observe the auroral emissions generated by Uranus's complex magnetic field interaction with the solar wind.

2.3.4 Guiding Question: Why Does the Sun and Its Environment Differ from Other Similar Stars?

The Sun with its solar system is only one of many stars with planetary systems in the Milky Way Galaxy. While the Sun is the only host that is known to harbor life, Sun-like stars are among the more abundant types of stars. While there are detailed observations about the Sun, the solar wind, and physical processes like solar flares and CMEs, these observations do not reveal what the Sun and heliosphere were like in the past, or what they will become in the future. Still, knowledge of physical processes that take place on the Sun help in the understanding other stars for which detailed observations do not exist.

The many new observations from the previous decade have placed the Sun and its surroundings in the wider context of astrophysics. The long, uninterrupted light curves of the hundreds of thousands of stars monitored by Kepler and the Transiting Exoplanet Survey Satellite (TESS) to find exoplanets have had a laudable side effect—the ability to detect stellar oscillation and do seismic studies analogous to early helioseismic studies of the Sun. These observations enable precise estimates of these stellar masses, their sizes and ages, and define true solar analogs that help place the Sun among the other stars. This revolution in Sun–star comparison has led to interesting conjectures related to the evolution of stellar rotation and magnetic fields, which indicate that the Sun is at the cusp of its dynamo being shut down. In general, older stars rotate more slowly, caused by the loss of angular momentum from stellar winds generated by global dynamo mechanisms. The rate at which the rotation period decreases with time, starting near the middle of a star's main sequence lifetime for Sun-like stars at about the Sun's current age. The observations suggest that stellar global dynamos begin to shut down when rotation becomes too slow to affect convection through weakened Coriolis forces, reducing the shear induced by differential rotation and, in the process, disrupting the global dynamo. Thus, the Sun is at the precipice of change, although the change is certainly slow on human timescales.

Magnetically speaking, the Sun is already much quieter than other G-type stars. Stellar brightness variations caused by starspots on other solar-type stars show larger variations than the Sun. The larger variations may be either because the Sun is permanently less active than other stars, or that its activity levels vary over many thousands or millions of years. The higher activity of the other solar-type stars is also seen in their flare rates. While the Sun typically has few white-light flares, this type of flare appears to be common in other stars. In the first 3 years of the TESS mission, nearly 1 million candidate flare events were detected in about 160,000 stars. Furthermore, stars very similar to the Sun can have super-flares, which are flares with energies significantly greater than the Carrington flare of 1859. Statistical studies of the rates of super-flares on Sun-like stars indicate the occurrence of X700-class to X1000-class flares once every 3,000 to 6,000 years. While these rates are long compared to civilizations, they are short compared to geologic timescales.

Similar to the interplanetary magnetic field in the solar system, stellar magnetic fields are frozen into their stellar winds. The constant wind stream carries the stellar magnetic field outward into the astrosphere, building up the astrospheric magnetic field. While stellar activity is relatively easy to detect, astrospheres are not. The Hubble Space Telescope has successfully observed astrospheres of nearby dwarfs using Lyman-αabsorption. Magnetic field measurements using Zeeman Doppler imaging have enabled modeling of the astrospheres using codes developed for the heliosphere.

Observations to date have revealed that astrospheres of similar stars can be quite different. The size of the astrosphere and the magnetic field strength depend on one hand on the stellar activity and on the other hand on conditions of the surrounding interstellar medium. Habitability of these planets is ultimately determined by the conditions within the astrospheres: Too many strong flares and CMEs could lead to the stripping away of planetary atmospheres, making them uninhabitable. Thus, the elation of the 2016 discovery of a rocky planet in the habitable zone of Proxima Centauri, the Sun's nearest neighbor, was tempered by the detection of a super-flare with total energy more than 100 times greater than the most powerful solar flare. While assumed common, the first X-ray observation of CMEs from a star other than the Sun was made by the Chandra Observatory.

Similarities and Differences Between Solar and Stellar Dynamos

Observations of stellar activity have revealed very different activity cycles, some very short and others long, apparently independent of stellar rotation rates (see Figure 2-23). Furthermore, multiple cycles including those resembling the Hale cycle have been detected. Explaining the differences in the activity cycles will require modeling efforts along with astroseismic observations of the star's age and tachocline structure.

Implications of Different Solar and Stellar Flare Rates, Amplitudes, and Distributions

The study of other stars helps put the Sun and solar activity in context. The Sun is just one star at a given age, while there are many more stars, some similar to the Sun, some different, at various stages of their evolution. While it appears that the Sun is quieter than other stars, our observations span only a miniscule portion of the Sun's history. More studies of an ensemble of solar twins adds to the current knowledge and drives forward the understanding of the Sun as a star.

The large flare rates, and the much larger energy in stellar flares compared with those on the Sun, is currently not understood. This is important for exoplanet habitability—although it is currently not known if superflares hinder or help sustain life. Uncovering the physics of large white-light flares require a deeper understanding of eruptive processes, including why the Sun has so few white-light flares. X-ray and UV observations of stellar flares combine with Zeeman Doppler imaging to identify their magnetic structure. It is also important to understand the conditions under which noneruptive flares occur, and to monitor the flare rates of known solar-type star systems with rocky planets in their habitable zones.

In astronomy, properties of the Sun are used as a baseline to describe stellar properties—stellar sizes, masses and luminosities invariably expressed in terms of the solar mass, radius, and luminosity—as are stellar metallicities.

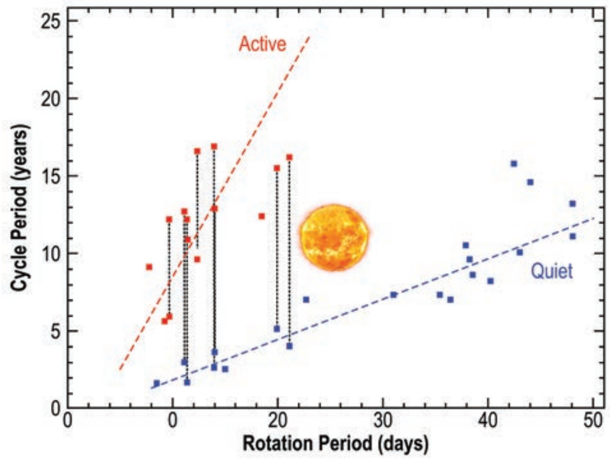


FIGURE 2-23 Observed relation between rotation period and cycle period of stars showing the active and quiet branches. Multiple cycles observed in the same star are connected with vertical dotted lines. The Sun's position in this cycle/rotation period diagram splits the difference between active and quiet stars.
SOURCES: Edited by AJ Galaviz III, Southwest Research Institute; From T.S. Metcalfe, R. Egeland, J. Saders, 2016, "Stellar Evidence That the Solar Dynamo May Be in Transition," *The Astrophysical Journal Letters* 826(1):L2, https://doi.org/10.3847/2041-8205/826/1/L2. Reproduced by permission of the AAS.

Understanding solar magnetic phenomena will, similarly, help in understanding phenomena related to magnetic activity of other stars, and what these phenomena do to the interplanetary media of those systems. To fully benefit from these studies, knowledge of Sun's magnetic phenomena at the poles, which is currently lacking, is urgently needed.

Differences Between the Heliosphere and Other Astrospheres

Comparing the heliosphere with other astrospheres requires concerted focus on observations and models. While Zeeman Doppler imaging observations, coupled with understanding of heliophysics enables modeling of other stars and astrospheres. These observations miss strong, small-scale magnetic features associated with flares and CMEs. Sun-as-a-star measurements (i.e., spatially unresolved measurements) to allow easy comparison with stellar data, while multiwavelength observations of stellar CME signatures (e.g., Hα, X-ray, and UV dimmings, radio bursts) resolve some of the current observational ambiguities. In parallel, heliospheric models (Figure 2-24) need to generate synthetic observations to quantify the detectability threshold and to facilitate comparison with observations, such as those from IMAP. Increased collaboration between the solar/heliospheric and stellar astrophysics communities provide opportunities for progress on these science challenges. One of the guiding questions of the decadal survey for astronomy and astrophysics was "How Do the Sun and Other Stars Create Space Weather?" (NASEM 2023), leading the way for formal cooperation between NASA's Heliophysics and Astrophysics divisions. Given that the scope of the Habitable Worlds Observatory line is now being assessed, solar and space physicists may play an important role in ensuring that knowledge of the Sun and the heliosphere are easily applied, overcoming the organizational barriers within NASA.

2.3.5 Guiding Question: What Internal and External Characteristics Have Played a Role in Creating a Space Environment Conducive to Life?

The existence of a magnetosphere has long been considered a defining feature of habitable or once-habitable planets. The strength of the magnetic field may indicate the difference between sustaining an atmosphere or losing one to the vastness of space. A magnetosphere funnels charged particles, harmful to lifeforms, toward the magnetic poles and away from other areas of the planet. The magnetic field also traps particles in nearby space and fuel

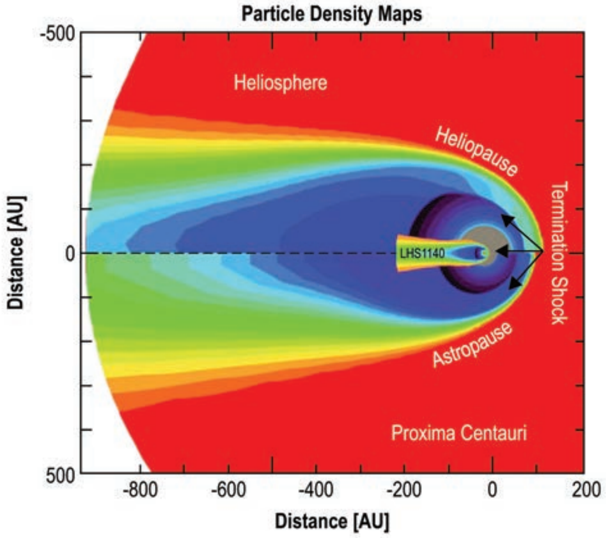


FIGURE 2-24 Direct comparison of the model results for the heliosphere (upper part), Proxima Centauri (lower part), and LHS 1140 (on top). The locations of the termination shock (TS) and the helio/astropause (HP/AP) are highlighted. The modeled heliospheric TS and HP distances are located at 90 au and 130 au, respectively. Red is high density and blue is low density.
SOURCES: Edited by AJ Galaviz III, Southwest Research Institute; From K. Herbst, K. Scherer, S.E.S. Ferreira, et al., 2020, "On the Diversity of M-star Astrospheres and the Role of Galactic Cosmic Rays Within," *The Astrophysical Journal Letters* 897(2), https://doi.org/10.3847/2041-8213/ab9df3. Reproduced by permission of the AAS.

danger zones that affect organic life and technology. The heliosphere plays a similar role in funneling high-energy charged particles toward or away from the planets.

Role of the Magnetosphere in Planetary Atmosphere Evolution

The MAVEN mission to Mars was designed to determine how the early warm and wet environment of the red planet transitioned to its current state of a cold, nearly dry rock. Initial studies concluded that significant atmospheric losses occurred early in Martian history, driven by intense solar storms. Without an internal magnetic field like that of Earth's, Mars transformed from a world potentially habitable to one incapable of supporting an atmosphere or life. However, later results suggest that outflow was increased by a global magnetic field concentrating particle precipitation at the poles. These results indicate that a working dynamo could have accelerated the loss of the Martian atmosphere. Thus, how exactly a magnetosphere contributes to sustenance or loss of a planetary atmosphere remains an open question. This question is answerable by careful comparisons of Earth's atmospheric loss with that of previously magnetized planets, such as Mars, and weakly magnetized planets, such as Mercury.

Role of a Magnetic Field as Shield from External Radiation

Understanding the fundamental plasma physics that occurs within planetary magnetospheres can provide a better view of these life-sustaining systems. One distinct way in which Earth's magnetic field protects life is by directing charged particles away from the low latitudes toward the poles of the planet. These solar particles are particularly energetic and therefore damaging to organic life during solar flares and storms. Because of Earth's strong magnetic field, most of these particles get funneled to the poles, away from population centers. Biological effects of energetic particle precipitation are not fully understood. However, radiation doses onboard polar airline routes are higher than previously suspected, making this funneling effect on human activity more important than previously thought.

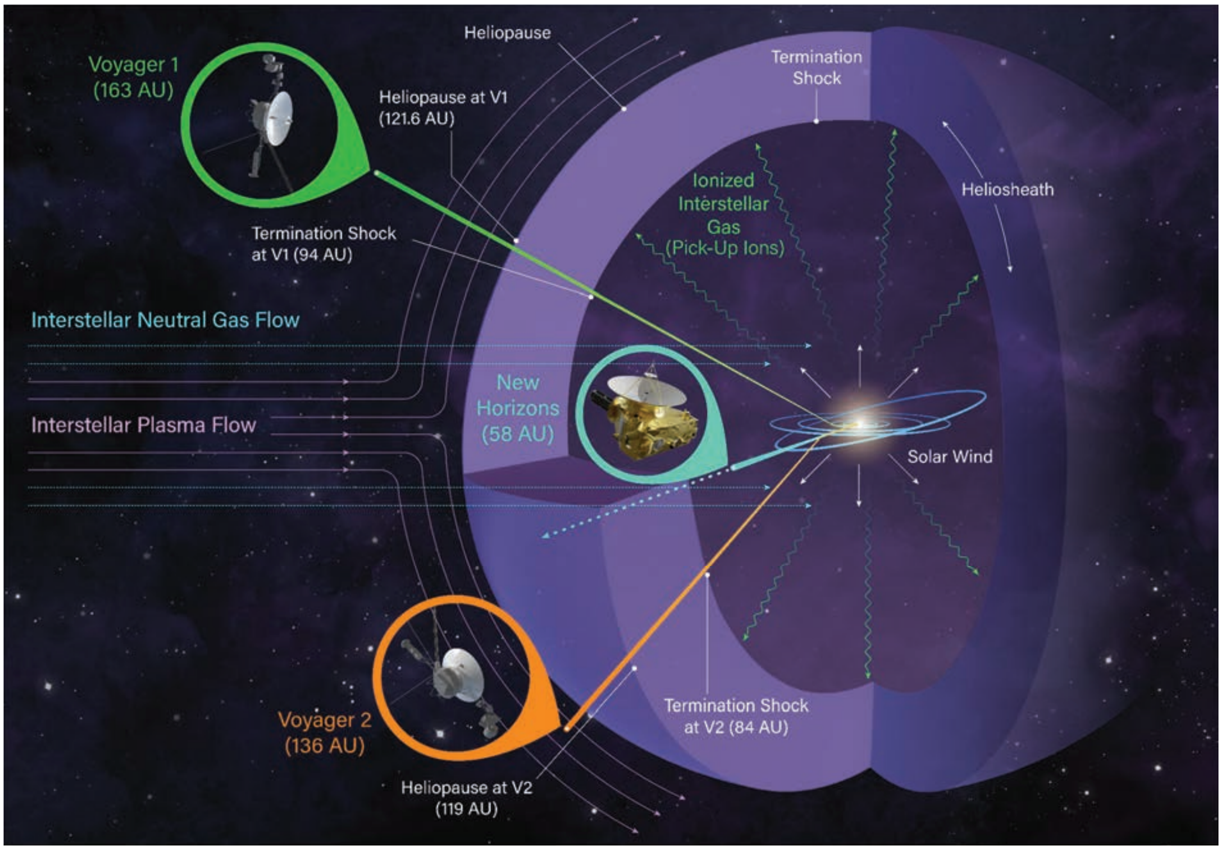


FIGURE 2-25 Exploration of the extreme boundaries of the heliosphere. In the future, the outstanding questions may be answered by exploring the extremes of magnetospheres at other planets, observing the interstellar medium and heliospheric boundary in more detail, and exploring the very local environment of the upper atmosphere at Earth.
SOURCE: S.M. Krimigis, R.B. Decker, E.C. Roelof, et al., 2019, "Energetic Charged Particle Measurements from Voyager 2 at the Heliopause and Beyond," *Nature Astronomy* 3:997, https://doi.org/10.1038/s41550-019-0927-4, reproduced with permission from SNCSC.

In a similar fashion, the interstellar medium continually buffets the heliosphere shielding, deflecting and focusing high-energy galactic cosmic rays from the habitable zone where Earth resides. The Voyager observations during traversal of the heliosheath (between the termination shock and the heliopause) answered a nearly century-old question about where the cosmic ray modulation boundary occurs. The Voyager spacecraft now provide direct measurements of the environment outside and reveal just how much the heliosphere attenuates external radiation (Figure 2-25). The IBEX mission probed the global heliospheric boundary revealing the large-scale influence of the interstellar medium on the morphology of the heliosphere. The upcoming IMAP mission will reveal more about the global, large-scale structure of the heliosphere, leading to better understanding of the role that heliospheric boundaries play in protecting the inner solar system from galactic cosmic rays.

Implications of Internal Particle Acceleration, Trapping, and Loss

Lower-energy radiation originating from the Sun gets trapped within planetary magnetospheres, including those of Earth and the giant planets (see Figure 2-26). Around Earth, these low-energy particles gain energy as they convect or are impulsively injected toward the planet. Trapped by the dipolar magnetic field, these particles

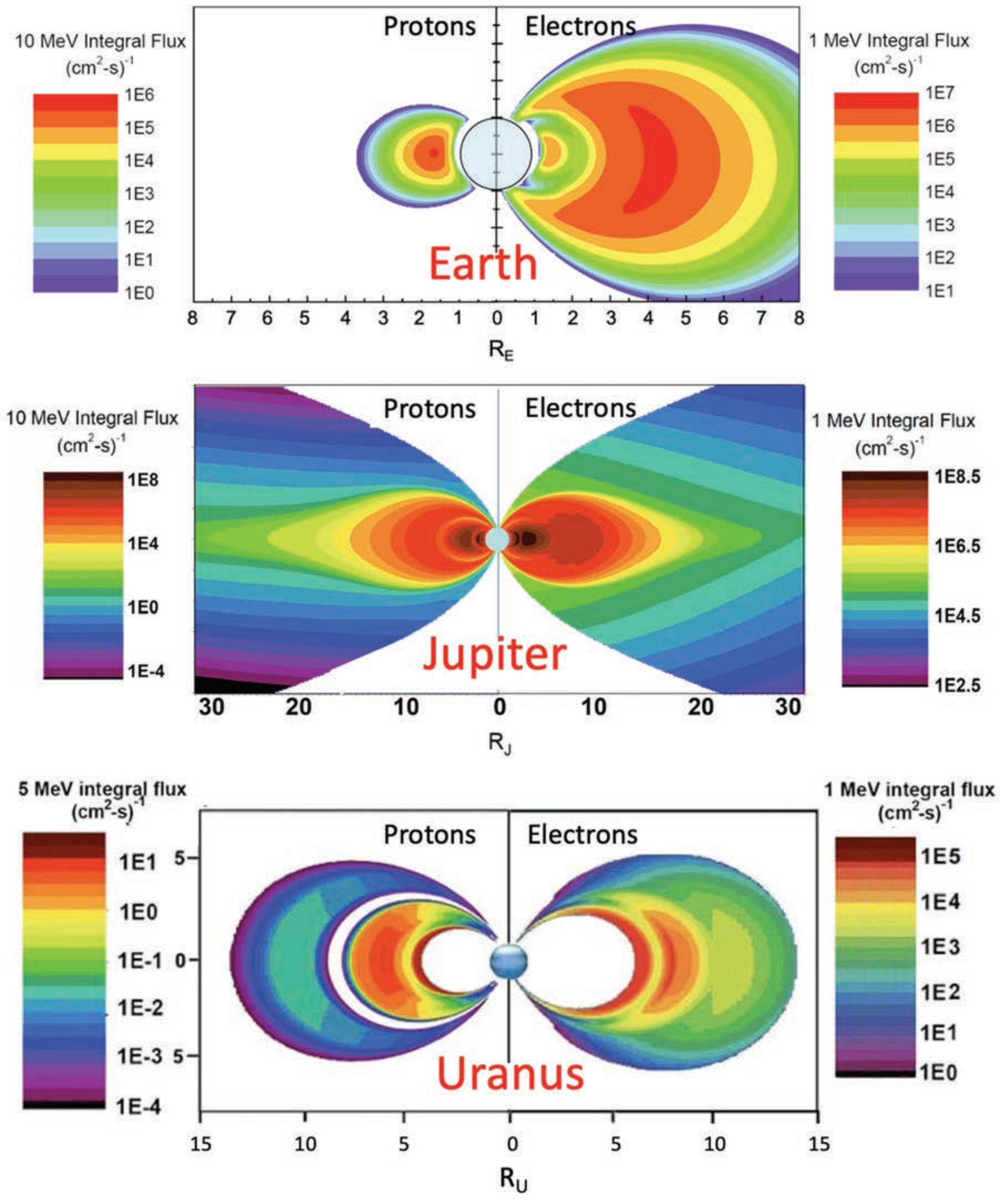


FIGURE 2-26 Proton (left side) and electron (right side) radiation belts at Earth, Jupiter, and Uranus. These comparisons show the diversity of radiation belts at the magnetized planets.
SOURCE: Based on I. Jun, H.B. Garrett, and R.W. Evans, 2019, "Trapped Particle Environments of the Outer Planets," in *IEEE Transactions on Plasma Science* 47(8):3923–3930, https://doi.org/10.1109/TPS.2019.2907069. Reprinted with permission from *IEEE Transactions on Plasma Science*.

form the radiation belts, with energies from many kiloelectronvolts up to megaelectronvolts. At Earth, trapped radiation is a hazard to space-based and ground-based technology (see Chapter 3). As these radiation belt particles rain down into the atmosphere, they result in changes in the electrodynamics and composition of the atmosphere.

Currents produced during geomagnetic storms are routed through long conducting materials, such as power lines, harming their operations. On the positive side, precipitation also causes the fascinating auroral displays, which have captivated human imaginations for centuries. Auroras now fuel interest in the outer planets. The Van Allen Probes mission contributed greatly to understanding the processes at work in Earth's radiation belts, and clues about processes in the Jovian radiation belt system have been provided by the ongoing Juno mission. These processes, following from solar wind-planet interactions, are important to understanding the evolution and history of life on Earth and other planets.

Future Missions

Missions to study the magnetic field systems of Jupiter, Saturn, Uranus, and Neptune would enable new comparative studies of magnetospheres. Each system is unique in the way that it controls particle acceleration and loss. For the atmospheric and climate implications, it is crucial to better explore the very local environment of the upper atmosphere at Earth. At a future time, these studies may be extended to the atmospheres of other planets—which will see very different effects from precipitation owing to their unique atmospheric and surface chemistries.

2.3.6 New Environments: Exploring Our Cosmic Neighborhood and Beyond—Theme 3 Synopsis

Table 2-3 summarizes the guiding questions, focus areas, and observational needs for Theme 3. Progress relies on having space physics instrumentation onboard planetary missions as well as making remote sensing observations of planets with astronomical telescopes, which is achieved through the ongoing, strong cross-divisional collaboration and coordination within the NASA Science Mission Directorate.

TABLE 2-3 New Environments: Exploring Our Cosmic Neighborhood and Beyond—Theme 3 Guiding Questions, Research Focus Areas, and Observations Needed to Carry Out the Research

Guiding Question	Focus Area	Observation Needs	Model Needs
What can we learn from comparative studies of planetary systems?	• Mass and energy flow processes driving planetary magnetospheres • Interactions of plasmas with solid body surfaces and atmospheres • Diversity of auroral processes	Particles and fields measurements throughout the magnetospheres of planets and their moons, ideally with synergistic multipoint observations. Measurements of fields and particles with composition near to solid surfaces/near to atmosphere/exosphere with concurrent observation of the neutrals in those regions. Remote sensing of aurora (ultraviolet [UV], visible, infrared, and radio) and in situ particles and fields measurements in polar regions of Uranus, and broadly distributed across Mars and Venus.	Magnetosphere models that predict electromagnetic and particle fluxes under different assumptions of the magnetic field strength and configuration. Magnetospheric models that explore effects of different plasma sources (e.g., planetary ionosphere, moons, solar wind).

continued

TABLE 2-3 Continued

Guiding Question	Focus Area	Observation Needs	Model Needs
Why does the Sun and its environment differ from other similar stars?	• Similarities and differences between solar and stellar dynamos • Implications of different solar and stellar flare rates, amplitudes, and distributions • Differences between the heliosphere and other astrospheres	Asteroseismic data on other stars to resolve their mass, age, and tachocline. X-ray and UV observations of flares in other stars. Zeeman Doppler imaging of other stars Sun-as-a-star observations in UV, X-ray. Near-simultaneous Hα, X-ray, and UV dimmings, radio burst observations of other stars.	Solar dynamo models expanded parameters of other types of stars. Models of the heliosphere that produce “Sun-as-a-star” synthetic observables to facilitate comparison with observations of other stars. Extension of heliospheric models to conditions around other types of stars and produce synthetic observables to compare with Sun-as-a-star data and quantify detectability thresholds.
What internal and external characteristics have played a role in creating a space environment conducive to life?	• Role of a magnetosphere in planetary atmosphere evolution • Role of a magnetic field as shield from external radiation • Implications of internal particle acceleration, trapping and loss	In situ particles and fields at other planets as well as Earth of the middle and lower atmospheres. Remote sensing and imaging of atmospheric components and outflow rates. Thermal and high energy particles, magnetic field, surface level measurements of planetary magnetospheres, heliospheric boundary, and interstellar medium. Particles across a wide range of energies from auroral to radiation belts at different magnetic planets. Accurate measurements of precipitation at Earth and other planets. Remote sensing and in situ measurements of neutral atmospheric constituents at Earth and other planets.	Detailed models of atmosphere–magnetosphere interactions under different assumptions of magnetic fields and atmospheric properties. Whole atmosphere simulations for Earth that have accurate particle precipitation as inputs. Diffusion models of wave-particle interactions within magnetized planets’ magnetospheres. Simulations of energy inputs to the atmosphere, including solar, electromagnetic, auroral precipitation, energetic particle precipitation, Joule heating effects, conductivity effects, neutral atmosphere dynamics and mesosphere–lower thermosphere effects including those of gravity and planetary waves.

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3

Solar and Space Physics in the Service of Humanity

3.1 INTRODUCTION: SPACE WEATHER—IMPERATIVE AND OPPORTUNITY

The solar flare on September 1, 1859, and its associated geomagnetic storm—the Carrington Event—is thought to be the largest space weather event ever recorded. Arcing from currents induced in telegraph wires caused fires in both the United States and Europe. (Cliver and Dietrich 2013)

On May 23, 1967, the Air Force prepared aircraft for war, thinking the nation's surveillance radars in polar regions were being jammed by the Soviet Union. Just in time, military space weather forecasters conveyed information about the solar storm's potential to disrupt radar and radio communications. (Knipp 2016)

The August 4, 1972, flare, shock, and geomagnetic storm are components of a Carrington-class event. The event was associated with a nearly instantaneous, unintended detonation of dozens of sea mines near Hai Phong, North Vietnam. The event also occurred between the Apollo 16 and 17 missions. Had astronauts been on the surface of or orbiting the Moon, they would have received a near-lethal radiation dose. (Knipp et al. 2018)

On March 13, 1989, the largest magnetic storm of the last century caused widespread effects on power systems including a blackout of the Hydro-Québec system. (Boteler 2019)

In 2002, communication disruptions from space weather are believed to have led to the tragic deaths of U.S. service members at the Battle of Takur Ghar in Afghanistan. (JHU APL 2024a)

On February 3, 2022, SpaceX Starlink launched and subsequently lost 38 of 49 satellites due to enhanced neutral density associated with a geomagnetic storm. (Fang et al. 2022)

Space weather—variations in the space environment between the Sun and Earth—directly connects humanity's well-being and geospace. Over the past decade, the need to understand and predict space weather has grown considerably driven by a burgeoning space industry and a society increasingly reliant on technologies that are vulnerable to its impacts. For example, with the advancement of launch technologies and miniaturization of spacecraft instrumentation, the number of active spacecraft orbiting Earth has grown from roughly 1,200 in 2013 to almost 10,000 a decade later, with more than 8,000 of these in low Earth orbit (LEO). This growth, combined with the highly variable upper atmospheric drag conditions that result from increased solar activity of the approaching solar maximum, underscores the critical need for improved scientific understanding and services for efficient space traffic management.

As the number of assets in space grows, the space weather user base has expanded beyond the traditional communication and Earth observation fields to encompass a wide range of public and private industries. In the past decade, the number of space weather customers subscribing to the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) products has grown by a factor of 2.5, from 30,000 to almost 80,000 (see Figure 3-1 and Box 3-1).

Another major development is the revitalization of crewed space missions with the National Aeronautics and Space Administration (NASA) Artemis program targeting a permanent presence on the lunar surface and, eventually, a crewed mission to Mars. The harsh and unpredictable radiation conditions outside Earth's shielding atmosphere and geomagnetic field challenge the solar and space physics community to provide an adequately detailed scientific basis for the monitoring, prediction, and protection mechanisms needed to protect the crew.

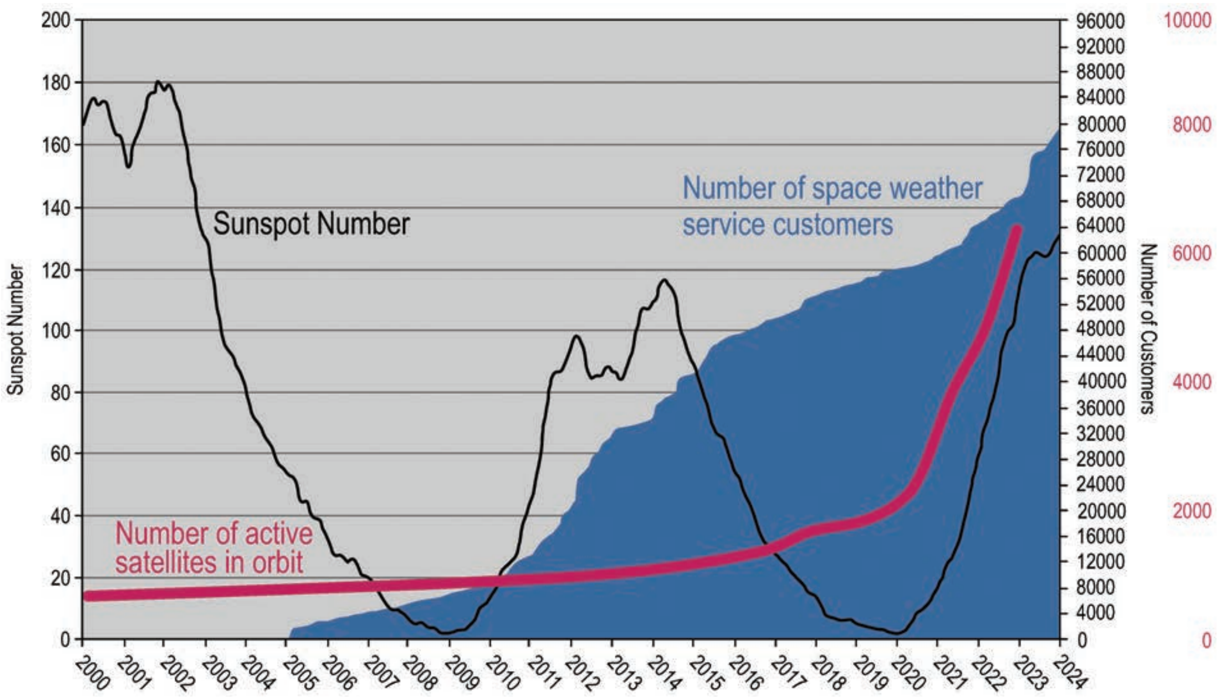

FIGURE 3-1 Growth of space weather services. This figure illustrates the large growth of the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) customer base (blue). This growth is expected to continue as the number of satellites in orbit grows exponentially (pink). While the large space storms associated with solar maximum are associated with extreme space weather, the growth of the customer base continued through the solar minimum around 2020 (as illustrated by the black curve showing the sunspot number).
SOURCES: Adapted from NWS/NOAA Space Weather Prediction Center (n.d.); Satellite data from J. McDowell (2024), https://planet4589.org. CC BY 4.0.

BOX 3-1
Space Weather Impacts from a Monthly-Occurring Storm to a "Once in 100 Years" Event

Starlink Event. In February 2022, medium-level solar activity caused a sequence of two moderate geomagnetic storms. SpaceX launched a batch of 49 Starlink satellites into the period following the peak of the first storm, with an intent to park the spacecraft on temporary orbits at 210 km altitude to be later raised to their final orbits. However, there is evidence that the increased atmospheric drag caused by storm-enhanced atmospheric density contributed to deorbiting and subsequent reentry loss of 38 of the spacecraft. This unfortunate event demonstrates the importance of considering space weather effects even during such relatively commonly occurring moderate events.

Carrington Event. In September 1859, English amateur astronomers Richard Carrington and Richard Hodgson recorded an impressive solar flare. The following day, Earth experienced history's most intense magnetic storm, with telegraph systems failing all over Europe and North America and auroral displays, normally confined to polar latitudes, visible in the tropics. Atmospheric charging lasted for more than a day, during which telegraph operators were not able to transmit or receive dispatches, but, instead, could unplug their batteries and transmit messages using only the power of the auroral current. An event of this magnitude today would cause immense damage to both ground- and space-based systems, and the recovery would take years and billions of dollars. A 2008 U.S. National Research Council report estimated that if a September 1859–size coronal mass ejection hit Earth now, the cost could be between $1 trillion and $2 trillion (in the first year alone) to repair the damage, and it could take 10 years to recover.

SOURCES: *Starlink event:* Fang. T.-W., A. Kubaryk, D. Goldstein, Z. Li, T. Fuller-Rowell, G. Milward, H.J. Singer, et al., 2022, "Space Weather Environment During the SpaceX Starlink Satellite Loss in February 2022," *Space Weather* 20:11, https://doi.org/10.1029/2022SW003193. *Carrington event:* National Research Council, 2008, *Severe Space Weather Events: Understanding Societal and Economic Impacts: A Workshop Report*, The National Academies Press, https://doi.org/10.17226/12507.

Advanced space weather services, such as predictions, warnings, and risk assessment (including worst-case scenarios), are based on scientific understanding of the interconnected "system of systems" that comprise the heliosphere, from solar eruptions (any episodic release of energy) to their impact on Earth's space environment, atmosphere, and infrastructure on the ground. Advances in space weather capabilities can only be achieved through new observations from the Sun to Earth, improved modeling of the systems and their interactions, and implementation of advanced technologies that go from observing systems to data distribution, computational models, and prediction systems. Thus, the solar and space physics community plays a critical role in the space weather enterprise. Indeed, space weather is inseparably tied to the science themes questions presented in Chapter 2.

The past decade was pivotal in how the federal government regards space weather. It is now widely recognized that developing the requisite understanding, observational systems, and services requires coordination and collaboration across federal and other agencies, commercial companies, and the research community, as well as other national and international players. It was also a pivotal decade because the federal government recognized that space weather is a related but separate endeavor from basic solar and space science research (seen, e.g., in the development of the 2015 National Space Weather Strategy and Action Plan and its 2019 update; NSTC 2023). This distinction was also recognized in the landmark 2020 Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT Act; P.L. 116-181), which, most importantly, also outlined the roles and responsibilities of key federal agencies and mandates that the agencies coordinate their activities across the different interest groups. The PROSWIFT Act did not authorize funds for implementation of the multiagency framework, and many of activities will require additional funding.

Recently, in December 2023, a memorandum of agreement (MoA) was signed by NASA, the National Science Foundation (NSF), NOAA, and the Department of the Air Force (DAF) to broaden the implementation of their space weather activities. With these coordination and collaboration structures in place, this decadal survey's statement of task considers space weather to be a central element of the strategy for solar and space physics.

Successful space weather predictions start from discovery research. The highest-priority research topics for the decade fall under the following three themes (see Figure 3-2) that capture the drivers, responses, and impacts of space weather:

- System of Systems: Drivers of Space Weather
- Space Weather Responses of the Physical System
- Space Weather Impacts on Infrastructure and Human Health

Unlike basic research, much of space weather research is focused on the development of information products that assist in economically significant decision-making, including national security, health, and safety. Thus, the research focus areas under these three themes are motivated by research outcomes rather than guiding questions, as is the case for basic research focus areas introduced in Chapter 2. The space weather research focus areas listed in Figure 3-2

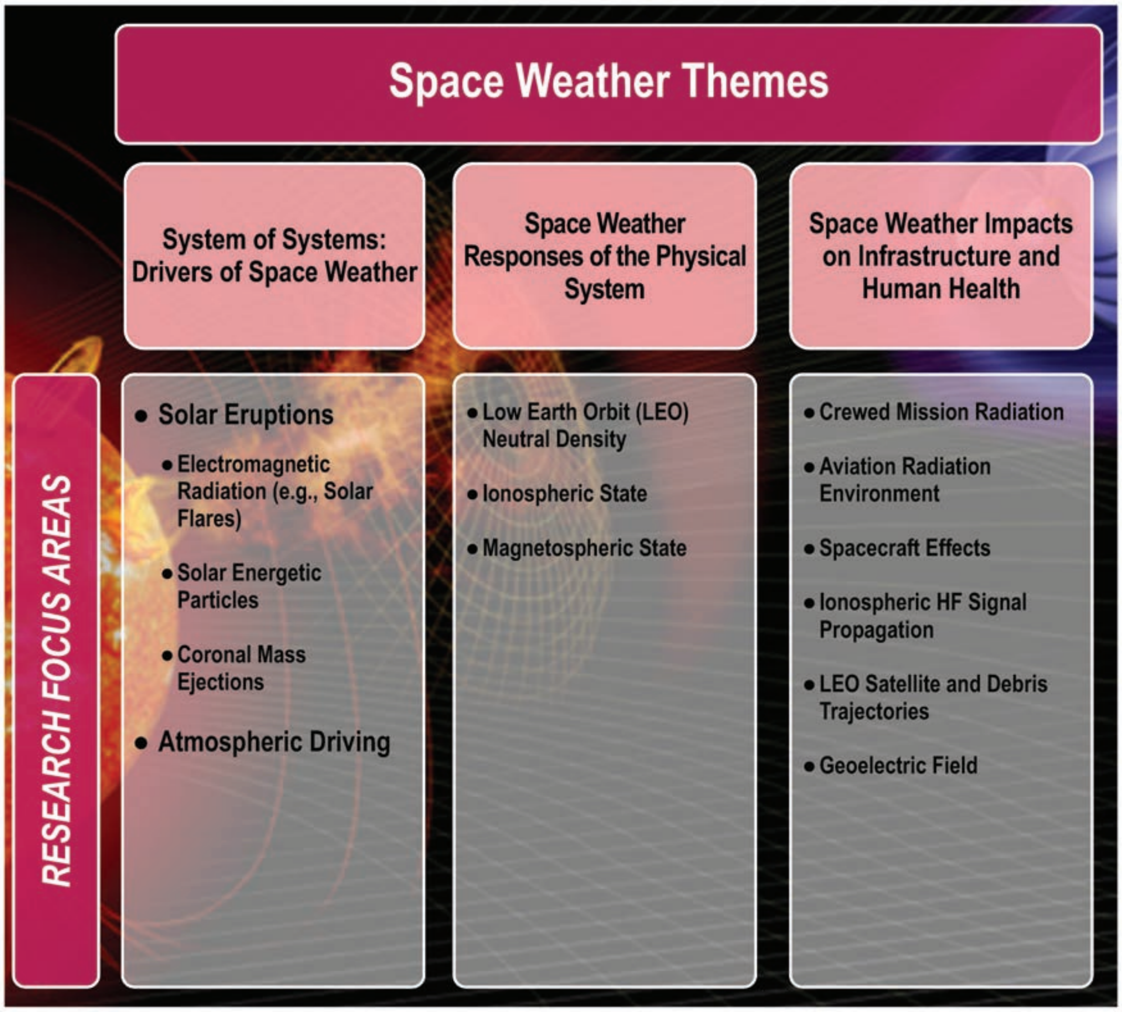

FIGURE 3-2 Space weather research themes and focus areas. Section 3.1 discusses each of the research focus areas, while Section 3.2 presents the overall strategy that makes significant progress in these focus areas.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Background image from NASA.

FIGURE 3-3 The space weather research to operations to research process illustrates the multiple steps needed before a basic research result is implemented as an operative service. Proving grounds and testbeds provide critical platforms for validation, performance demonstration, and user feedback.
NOTE: O2R, operations to research.
SOURCE: NOAA Space Weather Prediction Testbed, "R2O2R Overview," https://testbed.swpc.noaa.gov/r2o2r/r2o2r-overview, accessed May 21, 2024.

are the most compelling research needs identified for the next decade. However, prioritization of space weather research must be continuously assessed through a process that involves strong interaction between the research, operations, and user communities. This transition of research results to operations, and feedback from the users to the research community is referred to as the research-to-operations-to-research (R2O2R) cycle (Figure 3-3).

With sufficient investments, significant progress will be made on each of the space weather themes and their associated research focus areas in the next decade. Obtaining a multihour forecast capability for solar energetic particles (SEPs) would mean significantly reduced risk for human operations in space, be that in LEO or in the lunar environment. This multihour forecast capability is critical to the Artemis program and to future missions to Mars. The ability to forecast coronal mass ejection (CME) impacts and their magnetic field structure 24 hours in advance would enable spacecraft and power system operators to take mitigating actions, avoiding damage that can cost hundreds of millions of dollars (NRC 2008; Oughton 2018). Perhaps the fastest growing problem arises from the rapidly increasing number of spacecraft and debris in LEO. Space traffic management costs associated with collision avoidance are already significant; an ability to predict the thermospheric density would relieve some monitoring needs and reduce the risks and losses associated with the increasingly probable collisions in a highly crowded environment. Monitoring and modeling the LEO space environment, known as space situational awareness, is thus of critical importance for the next decade.

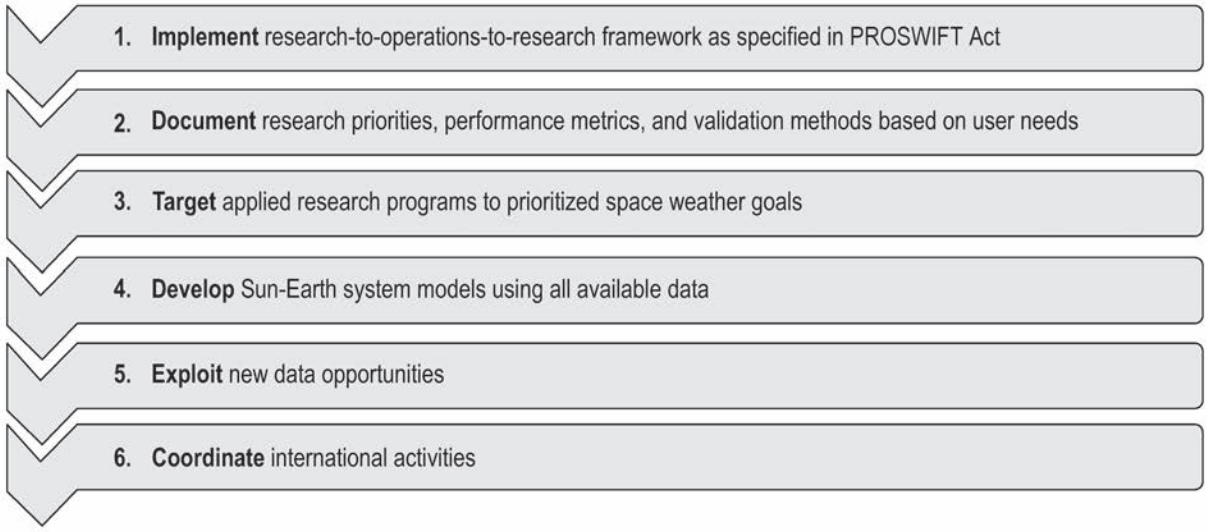

FIGURE 3-4 Six-element strategy for space weather. Each of these elements contains conclusions and recommendations detailed in Section 3.2 and integrated with the overall solar and space physics strategy in Chapter 5.

The space weather research strategy arising from the mission statement presented in Chapter 1 (see Figure 1-15) builds on the research-to-operations and operations to research framework as specified in the PROSWIFT Act. Effective use of resources requires documenting priorities and metrics of success as well as allocation of research funding to projects that develop the highest-priority applications. Priorities for investments in research and transition efforts must be based on assessments of expected impacts as well as the cost-effectiveness of the investments. The strategy includes both model development and creative use of emerging opportunities. Last, because space weather is a phenomenon with instantaneous effects worldwide, the best results will come from strong international collaboration. These considerations guided the development of a six-element space weather strategy as part of this decadal survey (Figure 3-4). While the National Space Weather Strategy and Action Plan (NSTC 2023) sets national priorities with detailed actions mandated in the PROSWIFT Act, the decadal survey strategy addresses those issues that have strong ties to the solar and space physics research community and have high potential for major advances in the next decade.

Parallel to the science themes and guiding questions introduced in Chapter 2, Section 3.2 provides a detailed discussion of the space weather research focus areas (see Figure 3-2). Many of these have significant fundamental research components and strong parallels to the science themes in Chapter 2. The remainder of Chapter 3 details the six elements of the space weather strategy introduced above (Figure 3-4) and includes all space-weather related conclusions and recommendations. The conclusions and recommendations are included in Chapter 3 so that it is a self-contained report on space weather aspects of solar and space physics. However, these strategic elements, while sharing science and operational components, have strong ties to the overall decadal strategy for solar and space physics, thus the space weather recommendations are referred to in Chapter 5 as part of the integrated research strategy.

3.2 SPACE WEATHER RESEARCH

With the recent increase in space-based activities and society's growing dependence on technologies vulnerable to space weather, there is a growing urgency to establish more efficient pathways toward improved scientific understanding of space weather phenomena and concomitant development of service capabilities. In the next decade, the solar and space physics community will contribute to the space weather enterprise by addressing research needs that are organized here into three broad themes:

- *Theme 1—System of Systems Drivers of Space Weather*. The renewed interest in crewed space exploration adds to the need of predicting the radiation environment from the upper atmosphere and LEO to the lunar environment and beyond. The Sun emits high-energy particles, plasma clouds, and photon radiation, each of which have their specific space weather impacts. Increasing the accuracy and lead time for a prediction of when a solar eruption will occur is imperative for mitigating the impacts of hazardous energetic particles that can reach Earth within only tens of minutes (see Figure 3-5). Advances needed to protect assets on Earth, and human life and technological systems in space, can only be provided through basic research addressing current knowledge gaps that often relate to connections between different regions, and across spatial and temporal scales.
- *Theme 2—Space Weather Responses of the Physical System*. The particles and plasma clouds that expand through space impact and interact with Earth's space environment through a variety of processes and at a range of very different timescales. These processes, together with processes in the lower atmosphere, influence the dynamical states of the magnetosphere, ionosphere, and atmosphere systems. To predict the state of the space environment from the atmosphere through interplanetary space, it is necessary to understand how the particles, plasmas, and fields travel from the Sun outward, and how they interact and influence the background solar wind, Earth's magnetosphere, ionosphere, and atmosphere.
- *Theme 3—Space Weather Impacts on Infrastructure and Human Health*. The variability in the space environment that is driven by space weather causes a variety of impacts on technologies in space, in the air, and on the ground as well as communication systems between space and ground. Understanding the impacts on specific systems and on humans onboard aircraft and in space requires modeling of the physical system impacts on technology and human tissue. Achieving such capabilities at the speed and reliability required for operational products calls for new advancements using high-performance computing, artificial intelligence, and data science.

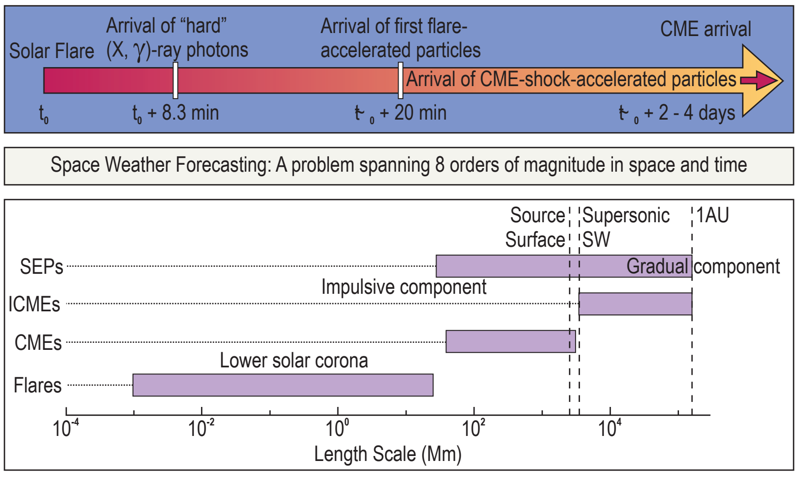

FIGURE 3-5 Spatial length and arrival times of a solar flare and associated energetic particles. Arrival times of the first flare-accelerated particles is tens of minutes, whereas the coronal mass ejection (CME) arrives in 2–4 days. If the CME is geoeffective (i.e., couples effectively with and has a dramatic effect on Earth's magnetosphere), then the recovery time for the magnetosphere is as long as a week.

NOTE: ICME, interplanetary coronal mass ejection; SEP, solar energetic particle; SW, solar wind.

SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Adapted from Georgoulis et al. (2024), https://doi.org/10.1016/j.asr.2024.02.030. CC BY-NC-ND 4.0.

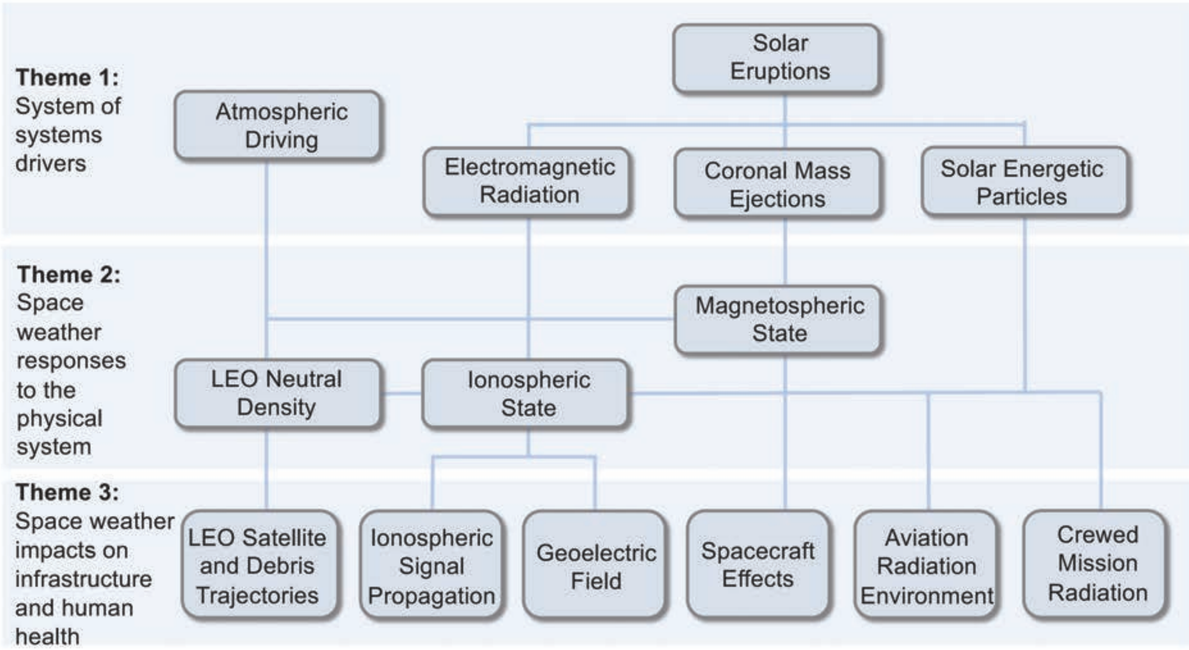

FIGURE 3-6 Space weather research themes follow the Sun–Earth connection process starting with solar inputs, through their effects on the physical system to their impacts on infrastructure and human health.

Figure 3-6 illustrates the space weather research themes as a flow chart from drivers to responses of the system, to impacts on technology and humans. The figure is not meant to illustrate the interconnectedness of the Sun–Earth system, but rather process flow embeds the research focus areas already introduced in Figure 3-2 and described in more detail below.

Figure 3-7 illustrates the multitude of space weather impacts that research must address in the next decade. While it is clear that avoiding collisions in LEO and protecting humans from radiation storms as humanity ventures further into space are high priorities for the next decade, the prioritization and sequencing of the integrated research strategy requires ongoing assessments of numerical modeling skill, infrastructure risk, and anticipated return on investment.

3.2.1 Theme 1—System-of-Systems Drivers of Space Weather

Solar Magnetic Eruptions and Solar Energetic Particles

Solar magnetic eruptions, or just solar eruptions, are any episodic release of energy and are the root cause phenomenon behind all extreme space weather (see Figures 3-2 and 3-6). They are the origin of solar flares that cause ionospheric disturbances, CMEs that drive geomagnetic storms impacting the entire near-Earth space environment, and SEPs that are known to disable spacecraft and damage human health. Furthermore, solar eruptions are phenomena capable of generating once in 100 years extreme space weather events that have the potential for creating worldwide disruptions that cost billions of dollars (NRC 2008).

Currently, the SWPC issues up to 72-hour probabilistic eruption forecasts, but even 24-hour forecasts have such high false alarm rates that their use in decision-making is limited. The critical need for improving predictions is amplified by the proliferation of LEO spacecraft and the renewed interest in crewed spaceflight beyond LEO, including establishment of a lunar base. Solar active regions can evolve into an eruptive state within 24 hours, putting severe limitations on what is feasible to achieve. However, given sufficient investments for research,

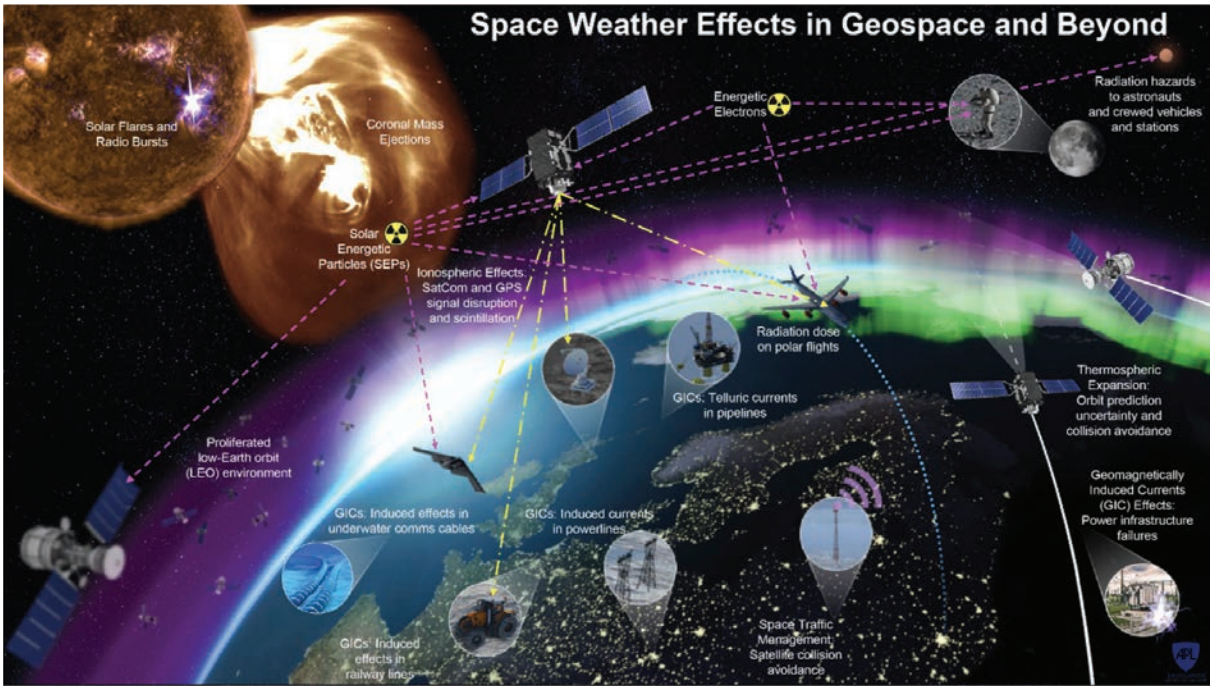

FIGURE 3-7 Space weather impacts are felt in space, on communications through the atmosphere, in the atmosphere, and on ground.
SOURCE: NASA (2021), compiled by APL.

machine learning eruption models combined with high-quality solar imaging have the potential to achieve accurate and actionable 12-hour eruption forecasts in the next decade. Even 6-hour SEP forecasts would facilitate better decision-making and mitigating actions for users such as those responsible for astronaut safety (Figure 3-8), spacecraft launches, and aviation route planning.

The outcome of this research focus area is the development of accurate, actionable, and reliable probabilistic forecasts of solar flares (>M1) with 12-hour lead time and of associated SEP events with 6-hour lead time. Achieving this lead time, accuracy, and reliability requires simultaneous, inter-calibrated, full-Sun (including the poles and all longitudes) measurements of the magnetic field and solar atmospheric structure combined with coronagraphic imaging. Advanced data assimilation methods are then able to track active regions over their lifetimes, establish magnetic connectivity to the solar source regions from any point in the inner solar system, and determine CME and energetic particle trajectories as they launch from the solar surface. SEP event predictions also require analysis of CME propagation from the Sun to Earth's environment (see below).

Coronal Mass Ejections

CMEs impacting Earth's space environment drive the largest geomagnetic storms and associated space weather impacts. The out-of-the-ecliptic interplanetary magnetic field (Bz) polarity and magnitude and the solar wind speed are the key attributes of a CME that drive explosive reconfiguration events. When a CME is "geoeffective," high-particle fluxes are produced in the magnetosphere, which are hazardous to space infrastructure and large electric currents in the auroral ionosphere and have the potential to damage power networks and disturb communications, navigation, and positioning systems.

Currently, the radial velocity of an Earth-directed CME is deduced from coronagraph observations to some degree of accuracy, which gives a lead time of 24–48 hours before the CME impacts Earth. However, the magnetic

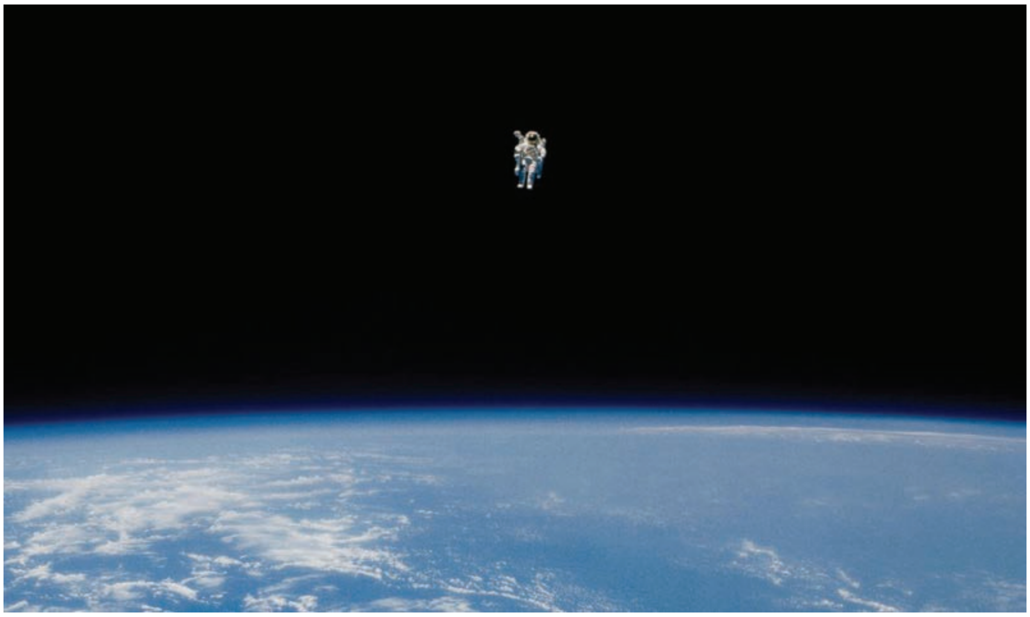

FIGURE 3-8 Space—the next frontier. Astronaut safety is critically dependent on the ability to monitor and forecast solar energetic particles in near-Earth space as well as in the lunar environment.
SOURCE: NASA (2024a).

field orientation is only measured in situ in the solar wind, and such observations available from the Lagrange point L1 provide only 30–60 minutes of lead time before arrival at Earth. While 24-hour geomagnetic storm severity forecasts desired by many users may be beyond reach in the next decade, any increase in the lead time will be a significant improvement. For example, spacecraft operators need lead times of 6 to 12 hours to anticipate impacts from a CME-driven space weather event.

The outcome of this research focus area is a 12-hour lead time forecast of the CME magnetic field and a 2–3 hour upwind nowcast of other CME characteristics. The magnetic field forecast requires continuous, multiviewpoint, remote observations of CMEs combined with realistic numerical models of their propagation through the solar wind. To improve accuracy, physics-based models need to be augmented with data using modern data assimilation techniques. The increased lead time for short-term nowcasts requires upstream measurements much farther from Earth than those currently made by solar wind monitors at L1 (1.5 million km from Earth) to 15 million km upstream, while improvements in accuracy and all-clear forecasts call for observations just outside Earth's magnetosphere.

Atmospheric Driving

The low-latitude region of Earth's upper atmosphere is confined to the dipolar region of Earth's magnetic field and thus is relatively well shielded from magnetospheric and solar wind variability. As a result of this shielding, the quiet time, low-latitude ionospheric scintillations that disrupt radio links are driven internally. Because these scintillations are not linked to geomagnetic storms, they may occur during both magnetically quiet and active periods.

Currently, it is thought that under magnetically quiet conditions, the major factor needed to destabilize the ionosphere and cause scintillation is the post-sunset enhancement of the equatorial- and low-latitude eastward electric fields and associated upward plasma drifts. The electric field responds to driving by the solar wind and magnetosphere (penetration electric field) from above, but also to complex forcing from the lower atmosphere. These effects are currently unresolved. Lower atmosphere waves and tides may contribute significantly to the quiet time post-sunset electric field, but the lack of full characterization of these waves and tides makes modeling of ionospheric phenomena challenging.

The outcome of this research focus area is to quantify how forcing from the lower atmosphere via gravity waves drives ionospheric scintillations. Including the scintillation drivers would enable critically important improvements to existing ionospheric correction models and avoid disruption of radio links used for civilian and military applications. Advancement in this research focus area requires investigation of the role of gravity waves for the formation of quiet time ionospheric disturbances. Advancement is only achievable through coordinated observations from heterogeneous space (first and foremost the Geospace Dynamics Constellation [GDC] and Dynamical Neutral Atmosphere–Ionosphere Coupling [DYNAMIC] missions) and distributed ground-based observation networks.

3.2.2 Theme 2—Space Weather Responses of the Physical System

Low Earth Orbit Neutral Density

Large geomagnetic storms (most often driven by CMEs) cause atmospheric upwelling and local density increases that cause spacecraft in LEO to lose tens of kilometers in altitude, leading to large deviations from their predicted orbits (Berger et al. 2023). The thermospheric neutral density is the largest source of uncertainty in satellite orbit predictions, and thus directly impacts safe operation of satellites.

In mid-June 2024, there were more than 9,000 spacecraft in LEO at altitudes between 400 and 1,200 km from Earth, two-thirds of which belong to Starlink, SpaceX's constellation (Faleti 2024). This total may increase by an order of magnitude or more in the coming decade (Falle et al. 2023). Such congestion leads to a vast space traffic management problem, which currently involves tens of hours of operator time spent each week tracking orbits of both spacecraft and debris, and planning mitigation actions (Figure 3-9). Furthermore, new missions face limitations of orbits usable to them because of this debris. This problem is sufficiently serious that it may jeopardize the use of LEO for space-based applications, which would be a tremendous setback for scientific research, university education, commercial activity, and public (environmental and other) services. Currently it is costing additional time and funds to continually replan orbits for research spacecraft. For example, the Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS) mission, which is still in development, is on its third orbit altitude replan since the Small Explorer (SMEX) mission was proposed.

There is a great need for accurate forecasts of thermospheric density changes during severe geomagnetic storms because these forecasts are used to estimate storm-time trajectory changes of LEO satellites and debris. Currently, NOAA SWPC uses the Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics (WAM-IPE) physics-based model that provides the thermospheric density and composition and includes the effects of solar activity.

The outcome of this research focus area is to develop an accurate and reliable thermospheric density model that incorporates advanced data assimilation capabilities and produces a 24–48 hour forecast of thermospheric density during geomagnetic storm conditions. This requires basic research to quantify the lower atmospheric influences on the ionosphere–thermosphere system—for example, through gravity and large-scale waves. To increase the forecast skill, prediction capability, and accuracy, physics-based modeling needs to be improved via data assimilation, artificial intelligence, and multimodel ensembles. Furthermore, additional environmental measurements are needed at LEO with good coverage in both altitude and latitude.

Ionospheric State and Magnetospheric State

As auroras are magnetically connected to Earth's magnetosphere, their dynamics and location serve as an indicator of the overall state of the space environment. The latitude of auroral boundaries is a proxy for energy input from the solar wind into the space environment and specifically into the ionosphere and thermosphere, while also revealing the regions on the ground where the most severe space weather impacts will occur. At low latitudes, enhanced intense and unstable ionospheric density structures during geomagnetic storm periods are a growing concern for many civilian, commercial, and military domains.

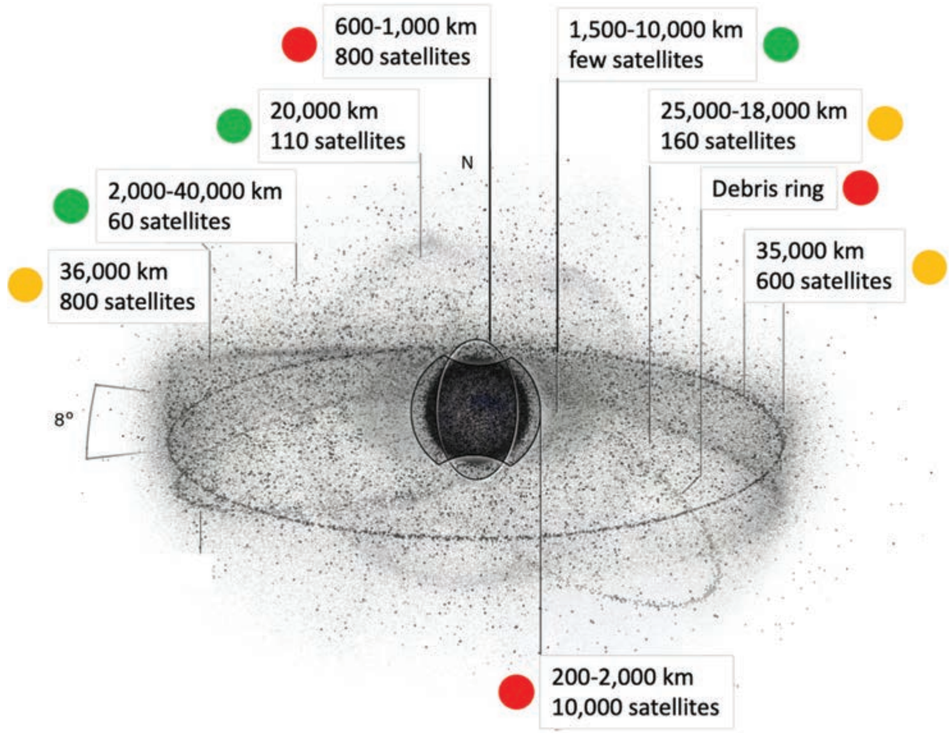

FIGURE 3-9 Space debris and urgency for mitigating actions. Low earth orbit is the most critical region both for the number of spacecraft, space debris, and sensitivity of the orbits to space weather impacts. The red, yellow, and green traffic lights indicate the urgency for mitigating actions to maintain operational safety. In the next decade, space weather research will contribute an accurate and reliable thermospheric density model to help develop mitigating actions.
SOURCE: Image courtesy of Pablo Carlos Budassi.

Current models for the auroral ionosphere lack the detail necessary for them to be used as inputs to models operated by the user community to gauge impacts. On the ground, the geoelectric field arising in response to auroral currents drives disturbances in power transmission networks, pipelines, undersea cables, railways, and other long conducting systems. Power transmission system impacts include reduced lifespan or failure of transformers, as well as voltage instability and possible collapse of regional networks.

Resolving the ionospheric structuring and dynamics at all latitudes is critical to technologies that rely on radio wave signals, be they satellite communication for positioning, navigation, and timing services or high-frequency communications that make use of signals reflected off the ionosphere. Enhanced electron density and structuring impacts signal paths, absorption, and noise throughout the globe, and thus may cause debilitating effects to operational systems.

The outcome of this research focus area is to develop a nowcast capability for comprehensive characterization of magnetospheric and ionospheric conditions, including SEP access; energetic particle and plasma transport, acceleration, and loss; auroral activity (e.g., its intensity, boundaries, and energy inputs); equatorial ionospheric dynamics and variability during sunset and sunrise; and preconditioning influences. Ionospheric and magnetospheric conditions can be monitored by a combination of ground- and space-based measurements, but only if these measurements have sufficient resolution and coverage.

Currently, ground-based instrument networks cover land areas very unevenly and do not cover the oceans at all. LEO satellites measure the state of ionospheric density as well as the precipitating particle populations that are needed to drive the ionospheric models. Polar cap potential specification using radar systems such as the

Super Dual Auroral Radar Network (SuperDARN) and field-aligned current measurements from satellite systems such as the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) are valuable for evaluation of the energy input rates. Similarly, ground measurements by heterogeneous instruments, such as the recommended Distributed Arrays of Scientific Heterogeneous Instruments (DASHI) network (see Chapter 5), provide key ionospheric state parameter fields (e.g., density variability and its driving mechanism) and their spatio-temporal coupling on multiple scales, thereby enabling transformative advances to nowcasting and forecasting capabilities. The Geostationary Operational Environmental Satellite (GOES) fleet monitors the magnetospheric state at geostationary orbit, but there are no missions monitoring the heart of the radiation belts inside geostationary orbit or the radiation environment and plasma acceleration processes outside geostationary orbit.

Reanalysis

Although not listed as a focus area of this particular theme, an important capability to develop over the next decade for all areas of Sun-Earth modeling is "reanalysis." Reanalysis refers to the process of creating a long-term reconstruction of the state space (i.e., the set of possible configurations) in the space weather environment, typically generated with data-assimilative numerical simulation models. End users of this process include, for example, vehicle anomaly analysts and designers, who use reanalysis to refine data from the past that determine either specific conditions during a past or ongoing mission or to establish cumulative and worst-case transient design environments. Reanalysis is also a key process in improving forecasting models. For example, when new data sources become available, or if previous errors in observations are identified and corrected, or when potential model improvements need to be validated, reanalysis of the state space over a given period (typically containing challenging events) serves to illuminate model performance gains or losses.

Currently, reanalysis in space weather is limited to a handful of studies reporting long-term numerical simulations—usually not data assimilative—with some simulating every storm during a long period of time. Such "free running model simulations" without data assimilation are not generally recognized as reanalysis runs, because they do not include improved input data or specific model improvements demonstrating superior state space specification.

The objective is development of a robust reanalysis capability for forecast or nowcast models with established community standard input data sets for all key space weather drivers and impacts. Advances in this research focus area require publicly accessible repositories of standard state space models of the magnetosphere and the ionosphere–thermosphere–mesosphere system, spanning many solar cycles. These reanalysis runs would be based on state-of-the-art numerical simulation models, either research or operational, and are expected to include data assimilation to correct the models to realistic states.

3.2.3 Theme 3—Space Weather Impacts on Infrastructure and Human Health

Crewed Mission Radiation

The outcome of this research focus area is to characterize and monitor the space weather environment in cis-lunar space and on the lunar surface in support of the Artemis program. For crewed missions, especially those outside Earth's magnetosphere, the primary space weather risk is the high fluence of energetic particle radiation that comprises the SEPs and the galactic cosmic ray population, which can cause both acute and long-term health impacts and damage spacecraft systems. NASA is currently expanding its crewed missions to the Moon and eventually to Mars, which creates substantial pressure on safeguarding both technology and humans in high-altitude space outside the shield provided by Earth's atmosphere and magnetic field. Whether the Moon is in the solar wind or within Earth's magnetosphere, it is directly exposed to SEPs. The Moon may also encounter energetic electron impacts, either from magnetotail reconnection events or from solar energetic electrons. To safeguard the infrastructure and crew in LEO, in the inner magnetosphere, or en route to or on the Moon requires continuous monitoring of the radiation environment in the entire space from the near-Earth region out to lunar orbit. Protecting corresponding systems on the way to Mars will require the capability to monitor the entire inner heliosphere, because the relative locations of Earth and Mars vary over the 24-month Martian year. The Lunar Gateway space weather instrumentation will characterize the radiation environment inside and outside of the vehicle and have the potential to improve understanding of the radiation impacts to systems.

Aviation Radiation Environment

The outcome of this research focus area is to develop an accurate and reliable aviation radiation nowcast and forecast for airline operators during large SEP events. The operators need forecasts of SEP timing, intensity, and spectra with sufficient lead time to take preventive action. The quantification of the lead time requires consultation with airlines. Furthermore, an accurate real-time model for the geomagnetic field is required to improve the accuracy of models in the high-latitude regions. Currently, uncertainties of the field configuration lead to errors of an order of magnitude in SEP flux estimates. Research is needed to improve the radiation transport models that describe the particle paths through the space environment and aircraft structures, as well as to assess the human radiation exposure and impacts on the aircraft electronic systems.

Spacecraft Effects

The outcome of this research focus area is to develop a reliable probabilistic forecast of surface charging (3-day lead time), internal charging (28-day lead time), single event effects (SEEs; 6-hour lead time), and event total dose (1-day lead time) for all orbits. Energetic particle penetration to the spacecraft internal parts can lead to discharge events that can damage or even disable the subsystems. Surface charging and discharging at solar panels lead to degradation and reduction of power production. SEE damage can occur when energetic protons penetrate spacecraft electronics, leading to bit flips that can cause unintended spacecraft operations. Satellite, human spaceflight, and launch operators need forecasts of these impacts with sufficient lead time to take mitigating actions. Such forecasts require knowledge of energetic particle fluxes both of solar origin and those accelerated within the magnetosphere.

Ionospheric High-Frequency Signal Propagation

The outcome of this research focus area is to develop 30-minute to 1-hour lead time forecasts of radio wave signal impacts throughout the ionosphere. User requirements are already pushing beyond current nowcast and forecast systems toward higher temporal- and spatial-scale nowcasts, with a need for more capable probabilistic forecasts. Basic research efforts are needed to develop coupled ionospheric models with sufficient resolution to capture key space weather impacts at regional and local scales. Observationally, this requires continuation of current ground-based operations, an expansion of ground-based coverage in key geographic areas, expansion of satellite-based radio occultation data sources, and an advancement of real-time systems to reduce data latency (across ground and space) to support operational systems. Current nowcast and forecast capabilities for the absorption of radio signals in the ionospheric D region, important for the aviation industry, will also benefit from improved solar energetic particle forecasts, as described above in Section 3.2.1.

Low Earth Orbit Satellite and Debris Trajectories

The outcome of this research focus area is to develop an integrated modeling framework for predicting LEO satellite and debris trajectories during geomagnetic storms that combines an accurate space weather environmental forecasting model, an advanced satellite forcing model, and a model that enables object track forecasting. As one element of the process, a dedicated mission to explore gas–surface interactions and forcing at different LEO altitudes and latitudes would be needed to specify the aerodynamics involved in the processes, which falls outside the scope of solar and space physics. A radar-tracking calibration satellite fleet providing baseline trajectories of well-calibrated objects would be beneficial for validation and calibration of both trajectory prediction models and thermospheric density models.

Geoelectric Field

The outcome of this research focus area is to develop a reliable probabilistic forecasting (1 hour) of geoelectric field with increased spatial resolution (200 km) for addressing space weather impacts on the ground. This will require completion of the national magnetotelluric survey, and a similar survey for the U.S.–Canada border region. Current models need improved spatial resolution to better characterize the regional impacts and direct measurements of the geoelectric field for model validation. Probabilistic forecast models are needed for grid operator use. Such forecasts require knowledge of the solar wind and interplanetary magnetic field orientation as well as monitoring of the ground magnetic field variations.

3.3 STRATEGY FOR THE NEXT DECADE

This section introduces the six strategic elements that comprise the conclusions and recommendations for space weather. These recommendations are part of an integrated research strategy for solar and space physics, thus are also referred to in Chapter 5.

3.3.1 Implementation of the Research-to-Operations-to-Research Framework

In December 2023, NASA, NOAA, NSF, and DAF signed an MoA outlining the collaborations needed to improve transitioning space weather research into operational forecasts and to enhance feedback from operational applications into research, known as R2O2R. The agreement builds on an earlier National Science and Technology Council Space Weather R2O2R framework document, which established a formal structure for the R2O2R enterprise (see Tables 3-1 and 3-2). The framework document also expresses the importance of communication and collaboration between federal departments and agencies, academia, commercial enterprises, customers, and international organizations.

> *Conclusion: The NOAA-NASA R2O2R framework agreement, together with the quad-agency MoA between NOAA, NASA, NSF, and DAF, will facilitate the transition of new developments in space weather research to operational services and address the existing communication gaps between the user and research communities, as specified in the PROSWIFT Act.*

These agreements outline formal actions to be conducted, including prioritization of user needs and agency actions based on estimated return on investment, transition of research capabilities into operations, enhanced coordination between research modeling and forecasting centers, and communication of operational needs among the agencies. Full implementation of this framework will be essential for significant progress on the space weather research focus areas in this decadal survey (see Figure 3-2). This decadal survey does not provide specific guidance on how the agencies should implement the R2O2R framework. Rather, as outlined in this chapter, it provides a strategy to ensure that research and development efforts are focused on high-impact, high-priority needs with an R2O2R framework that will address critical national needs.

An important focus of the PROSWIFT Act is the acquisition and dissemination of space weather data. Specifically for NSF, the PROSWIFT Act requires the agency to

> (1) Make available to the public key data streams from the platforms and facilities . . . for research and to support space weather model development; (2) develop experimental models for scientific purposes; and (3) support the transition of the experimental models to operations where appropriate.

Furthermore, the Act calls for NSF to "continue to provide space weather data through ground-based facilities, including radars, lidars, magnetometers, neutron monitors, radio receivers, aurora and airglow imagers, spectrometers, interferometers, and solar observatories."

TABLE 3-1 Recent National Space Weather Policy Objectives

Year	Document	Source	Objective
2015	National Space Weather Strategy and Action Plan	National Science and Technology Council (NSTC)	Integrate national space weather effort
2016	Executive Order—Coordinating Efforts to Prepare the Nation for Space Weather Events	White House	Define roles and responsibilities for federal agencies, Office of Science and Technology Policy, and OMB
2016	Charter of the Subcommittee on Space Weather Operations, Research, and Mitigation (SWORM)	Committee on Environmental, Natural Resources, and Sustainability, NSTC	Establish SWORM subcommittee as the interagency body to coordinate federal departments and agencies
2019	National Space Weather Strategy and Action Plan	NSTC	Identify strategic objectives and actions to achieve a space-weather-ready nation
2019	Federal Operating Concept for Impending Space Weather Events	Department of Homeland Security	Prepare for and respond to space weather events
2020	Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act	P.L. 116-181, 116th Congress	Prepare and protect against social and economic impacts of space weather
2021	U.S. Space Priorities Framework	White House	Bolster the health and vitality of the U.S. space sectors
2022	Space Weather Research-to-Operations and Operations-to-Research Framework	Committee on Environmental, Natural Resources, and Sustainability, NSTC (SWORM Subcommittee)	Establish formal interagency structure for effective R2O2R
2022	Space Weather Roundtable	P.L. 116-181	Established to facilitate understanding of science and to enhance space weather forecasting capabilities

Conclusion: Implementation of these actions will span and require collaboration across multiple NSF divisions. New research infrastructure, such as the next generation Global Oscillations Network Group (ngGONG), the Frequency Agile Solar Radiotelescope (FASR), and the ground-based DASHI, would bring significant new contributions to observing the space weather drivers and impacts, as strategic assets of the R2O2R framework.

Recommendation 3-1: The National Science Foundation should develop an agencywide strategic space weather plan. The plan, as directed by the PROSWIFT Act, should include the incorporation of data streams for space weather purposes from both currently available ground-based facilities and networks, as well as those that would become available after implementation of the decadal survey's recommendations for ground-based observations. It should also support experimental model development and transition to operations. The development and implementation of the strategic plan is likely to require augmentations to the current level of effort and budget.

Following this strategy would imply that NSF would seek to expand and augment the current ground-based assets under NSF management into a coordinated, heterogeneous instrument network with specific contributions to space weather. Further contributions by NSF could be funding for developing near-real-time space weather data streams and for making those publicly available (see the PROSWIFT Act). Recognizing the strong ties between

TABLE 3-2 Space Weather Roles of Government Agencies as Defined in the 2020 PROSWIFT Act

Agency	Role
Department of Defense	Supports operational space weather research, monitoring, and forecasting for the department's unique missions and applications.
Department of the Interior	Collects, distributes, and archives operational ground-based magnetometer data in the United States and its territories, works with the international community to improve global geophysical monitoring, and develops crustal conductivity models to assess and mitigate risks from space weather-induced electric ground currents, as well as provide data to improve geomagnetic field models (e.g., the Water Measurement Manual) that are used for operation.
Federal Aviation Administration	Provides operational requirements for space weather services in support of aviation and coordinates these requirements with the International Civil Aviation Organization and integrates space weather data and products into the Next Generation Air Transportation navigation and communication Systems.
National Aeronautics and Space Administration	Provides support to increase the understanding of the fundamental physics of the Sun–Earth system through basic research, space-based observations, and modeling, developing new space-based technologies and missions, and monitoring of space weather for NASA's space missions.
National Oceanic and Atmospheric Administration	Provides operational space weather monitoring, forecasting, and long-term data archiving and access for civil applications, maintains ground-based and space-based assets to provide observations needed for space weather forecasting, prediction, and warnings, provides research to support operational responsibilities, and develops requirements for space weather forecasting technologies and science.
National Science Foundation	Provides support to increase the understanding of the Sun–Earth system through ground-based measurements, technologies, and modeling.

SOURCE: Data from "Title 51–National and Commercial Space Programs." Pub. L. 111-314, §3, Dec. 18, 2010, 124 Stat. 3328.

basic research and space weather application development, NSF is encouraged to continue its current efforts to support space weather research in all parts of the chain, including fundamental physical processes, model and method development, transition to operations, and application development, to meet the PROSWIFT Act mandates.

3.3.2 Documentation of Research Priorities, Performance Metrics, and Validation Methods

The growing investments in space weather are a direct response to the growing need for space weather services to protect national infrastructure, improve economic activity, and safeguard lives and property. In a cost-constrained environment, it is important that strategic investments focus on the highest-priority service needs and areas where the most significant benefits can be realized.

Tangible progress on space weather services needs to be based on knowledge of the impacts and customer actions that will be enabled by the enhanced services (Table 3-3). The foundation for prioritizing R2O2R activities is a quantitative assessment of current capabilities and an understanding of the gaps between current capabilities and the needs of industry and government. For such an assessment, it is critically important to have a comprehensive and objective set of performance metrics and validation methods to evaluate the performance of models and service products as well as to quantify their significance for customer mitigation actions and economic impacts. Such metrics need to be developed by the operational agencies and industry. These metrics can then be used to set research priorities that are informed by identification and prioritization of the capabilities that are the most urgent and for which substantial progress can be expected within the next decade.

The rapid growth of space weather users and the swift changes of their needs calls for frequent communication about the capabilities and gaps between customers and industrial and academic partners. The service requirements need to be continuously updated as technologies and applications evolve, and as new mitigation measures are employed.

TABLE 3-3 Recent Assessments of Economic Impacts, Customer Needs, and Gaps

Impact Area	Economic Impacts[a]	Customer Needs[b]	NASA Gap Analysis[c]	Benchmark Report[d]
Electric Power	✓	✓	✓	✓
Satellite Radiation/Charging	✓	✓	✓	✓
Navigation	✓	✓	✓	✓
Communication	✓	✓	✓	✓
Aviation	✓	✓	✓	
Agriculture	✓	✓		✓
Emergency Management		✓	✓	
Satellite Collision Avoidance			✓	✓
NASA Robotic Exploration			✓	
NASA Human Exploration			✓	

[a] Abt Associates. 2017. "Social and Economic Impacts of Space Weather in the United States." Bethesda, MD. https://www.weather.gov/media/news/SpaceWeatherEconomicImpactsReportOct-2017.pdf.

[b] Abt Associates, Inc., U.S. National Weather Service, Space Weather Prediction Center. 2019. "Customer Needs and Requirements for Space Weather Products and Services." Rockville, MD. https://repository.library.noaa.gov/view/noaa/29107.

[c] Johns Hopkins University Applied Physics Laboratory. 2021. "Space Weather Science and Observation Gap Analysis for the National Aeronautics and Space Administration." Laurel, MD. https://smd-cms.nasa.gov/wp-content/uploads/2023/11/gapanalysisreport-full-final.pdf.

[d] Reeves, G., Institute for Defense Analysis—Science and Technology Policy Institute. 2019. "Next Step Space Weather Benchmarks." IDA Group Report NS GR-10982. Alexandria, VA. https://www.ida.org/-/media/feature/publications/n/ne/next-step-space-weather-benchmarks/gr-10982.ashx.

Conclusion: The PROSWIFT Act tasks the Space Weather Advisory Group (SWAG) to conduct a user survey, to be reevaluated not less than every 3 years, to "assess the adequacy of current federal government goals for lead time, accuracy, coverage, timeliness, data rate, and data quality for space weather observations and forecasting." As these surveys are currently in the planning stage, the results needed for prioritization of activities are not yet available, and the research community lacks a clear set of targets to work toward.

Recommendation 3-2: The National Oceanic and Atmospheric Administration (NOAA) and the Department of Defense (DoD) should build upon the periodically repeated Space Weather Advisory Group surveys of space weather product users to document the highest-priority customer needs and the best performance metrics and validation methods for available space weather applications. The results should be used to identify high-priority space weather research goals. In addition, processes should be developed to ensure communication of these priorities across NOAA, DoD, the National Aeronautics and Space Administration, and the National Science Foundation to be used when setting research priorities in the agencies' space weather–related programs.

Based on (1) an established process to communicate with industry and government to understand their space weather needs; (2) documentation of the performance metrics and validation information for operational models and products; and (3) identification of potential mitigating actions that could be taken with improved space weather information, it is then possible for NOAA and DoD to recommend priorities for near-term and long-term service targets. It is expected that the validation of research models will continue to be supported by NASA and NSF.

Conclusion: This decadal survey outlines a number of important research focus areas that are not further prioritized owing to lack of accurate understanding of current and future user needs. However, the decadal survey committee recognizes the growing space traffic management problems at LEO caused by increased number of spacecraft and debris as a critically important issue. Future mitigation actions will likely include regulation for faster deorbiting of post-operational spacecraft, which will increase the total costs and require *new technology development for deorbiting spacecraft without propulsion. Unless carefully implemented, such regulation can be particularly harmful to university and other academically oriented groups launching CubeSats, whose impact to the space traffic management problem will in all cases remain small if not insignificant.*

3.3.3 Targeting Applied Research Programs

Space weather, as with many other application-oriented disciplines, has its genesis in basic research. The solar and space physics community has established a solid foundation of scientific understanding—numerical models have been developed, and a Sun-to-Earth observing infrastructure is in place. To serve space weather users, further efforts are needed that center on applied research and innovations that convert this basic understanding into specific applications. New sophisticated techniques are needed for optimizing available data and models for space weather forecasts.

Current targeted research programs—such as NSF's Advancing National Space Weather Expertise and Research toward Societal Resilience (ANSWERS) and those supported by NASA's Living With a Star (LWS) program, Space Weather Program, and Heliophysics Research Program—provide valuable opportunities for the research community to focus on science questions that advance space weather capabilities.[1] Targeted funding from NOAA—and to some extent the Air Force Office of Space Research—has supported important research-to-operations transition and application development efforts. However, as each agency operates based on its own priorities, the current funding structure does not have mechanisms in place to prioritize the targeted research and development efforts according to the highest-priority customer needs.

Conclusion: By coordinating the space weather research programs of NASA, NSF, NOAA (see Recommendation 3-4), and DoD, the national research effort will focus on the highest user needs, and it will effectively integrate advances in basic science into the development of targeted applications.

Conclusion: The increased importance of space weather has created growing workforce needs in areas of application development, research to operations transitions, mitigation planning, and execution. Stable, coordinated applied research programs help to create healthy career paths for applications-oriented space weather research to meet the workforce needs.

Recommendation 3-3: National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) space weather research programs (such as NSF's Advancing National Space Weather Expertise and Research toward Societal Resilience [ANSWERS] and NASA's Heliophysics Space Weather Programs) should be targeted to prioritized space weather goals (see Recommendation 3-2).

The research priorities set according to the customer needs will be identified through the user surveys conducted by the SWAG and through other user surveys and government efforts (Recommendation 3-2). Initial priorities will likely include prediction of solar eruptions, SEP forecasts, and improved models for the neutral atmosphere to address the current issue regarding space debris.

3.3.4 Developing Sun–Earth System Models Using All Available Data

The dynamical environment from the Sun to Earth is an interconnected system of systems that can only be understood and accurately predicted when treated in its entirety. The complexity of the drivers, responses, and impacts in the space weather system call for approaches that invoke state-of-the-art modeling, data assimilation and data science methods, and artificial intelligence applications. A resilient infrastructure for real-time data taking and distribution, as well as forward-looking instrument technology development, are needed to support current and future operational space weather requirements.

[1] This paragraph was modified following the release of the report to accurately reflect NASA's targeted research programs.

Assimilative system models have accelerated progress in operational forecasting in Earth science, and such methods are now entering the Sun–Earth system modeling and space weather enterprise. The data scarcity problem in space weather science is twofold. While the vast space environment remains grossly under-sampled, current models under-utilize the available data owing to lack of assimilative methods and computational processing power as well as real-time data acquisition and distribution processes.

Conclusion: Society's space weather needs are served by combining in situ and remote sensing, space- and ground-based observations, and state-of-the-art models that focus both on modeling from the Sun out to the heliosphere and from the Earth system to space. This combination would provide space weather end users with accurate, on-demand resources to predict the consequences of space weather on systems distributed on and around Earth and throughout the solar system.

New needs for such efforts include the increased presence of humans and infrastructure beyond LEO (with particular focus on radiation dose) and increased commercial space activity in LEO (with particular focus on neutral density variations). The increased presence of humans in outer space requires characterization and monitoring of the space weather environment in cislunar space and on the lunar surface, and later en route to Mars and on the Martian surface. Modeling efforts would likely focus on the SEPs and the radiation environment in general. However, these efforts would also encompass the plasma effects arising from large solar eruption events. Space traffic management and broader space situational awareness at LEO requires improved understanding of variations, especially of the thermospheric density in response to solar and magnetospheric activity. Space weather research and modeling programs make important contributions to these high-priority efforts.

Conclusion: The development of advanced data assimilation capabilities is important for conducting observing system experiments (OSEs) and observing system simulation experiments (OSSEs) that quantitatively determine the value of observations for accurate specifications and forecasts. These new data assimilation capabilities are important not just for improving research and operational services, but also for their ability to inform decisions on future investments in the observing system, which is a capability is currently lacking.

Different from that of large-scale science models, space weather modeling efforts are focused on transition to operations, development of new models to meet particular user needs, as well as development of tools that address the quality and improvement of the forecasts. Besides physics-based modeling, these efforts often employ other methods, including data assimilation, artificial intelligence methods, and ensemble modeling. These models make use of the growing availability of distributed ground-based and space-based observations from research and operational missions and instruments, and from national, international, and commercial providers. The contribution of individual data sources to forecast and specification accuracy is quantified through OSEs and OSSEs, and through reanalysis of past observations.

Recommendation 3-4: The National Oceanic and Atmospheric Administration should establish a space weather research program. It should partner with the Department of Defense to develop large-scale predictive space weather models that can meet operational requirements, which may differ from those of scientific research models. Model development should make use of the versatile set of available space weather data.

In some cases, space weather modeling may be able to leverage or benefit from synergies with the science modeling efforts. In other cases, space weather models with specific user-driven applications, may need to be developed from scratch.

3.3.5 Exploitation of New Data Opportunities

Accurate and timely space weather services rely on numerical models driven by near-real-time observations from the relevant parts of the Sun–Earth system. NOAA has an operational satellite fleet (Figure 3-10), and NASA

FIGURE 3-10 NOAA Space Weather operational fleet.
SOURCE: Modified by AJ Galaviz III, Southwest Research Institute from NOAA (2024).

has operated some of its research spacecraft in an operational mode for 2 decades. New opportunities will arise from combining these assets with information from NSF ground-based facilities, international missions, and commercial providers. However, these heterogeneous data sets require careful intercalibration as well as new methods for data access and incorporation into the models.

NASA's LWS program targets basic research problems that have direct relevance to space weather. To some extent, the NASA Heliophysics System Observatory, which targets fundamental research questions, also provides near-real-time data for operational space weather services. The new Space Weather Program within NASA's Heliophysics Division is an ideal vehicle to test and validate concepts and to demonstrate the value of measurements that would then be candidates for long-term acquisition through operational systems.

In the next decade, the exploitation of data for space weather research will take advantage of both NASA's and NOAA's satellite fleets. NOAA's planned space weather observations portfolio includes operational monitoring from multiple locations, including the L1 and L5 Lagrange points (in partnership with the European Space Agency [ESA]), geostationary orbit, LEO, and highly elliptical orbits as well as input from ground-based observations.[2] Of these, LEO observations are still largely lacking, while they will be critically important for the development of atmospheric density and broader ionosphere–thermosphere models. However, LEO observations from NASA's GDC and DYNAMIC missions helps fill in this shortcoming. This NASA-NOAA partnership is one example of many partnerships that exploit capabilities of several agencies. NOAA's program will be carried out in partnership with other government agencies, international partners, and commercial providers. As the combined observing infrastructure of all the partners evolves beyond current capabilities, it will be a substantial research task to quantify the societal and economic advantages of these investments to justify long-term operational support.

Data purchases from commercial providers is an emerging opportunity that has the potential to significantly expand space data coverage, especially at LEO (see Table 3-4). As the number of commercial satellites increases, the opportunities to include space weather instruments on spacecraft in distributed orbits also increases. If the

[2] Some of these observations were mandated by the PROSWIFT Act. See Lugaz (2020).

TABLE 3-4 NOAA's Commercial Data Program

Years	Opportunity	Purpose
2016–2018	Commercial Weather Data Pilot Round 1: Radio Occultation Data	Seeks on-orbit radio occultation data from commercial sources for the purpose of demonstrating data quality and potential value to NOAA's weather forecasts and warnings. Space weather requirements were not included.
2018–2019	Commercial Weather Data Pilot Round 2: Radio Occultation Data	Similar to Round 1, but with space weather ionosphere measurements included as nonmandatory proposed specifications. Ionosphere total electron content measurements were provided and assessed.
2020–2022	Commercial Purchase: Radio Occultation Data Buy 1	Ionosphere measurements were not required, but considered as examples of capabilities that may be considered for purchase. Ionosphere total electron content measurements were provided and assessed.
2022–2027	Commercial Weather Data Pilot Round 3: Space Weather Data	Seeks measurements from Global Navigation Satellite System receivers that will enable derivation of ionospheric products that meet the needs of operational space weather models and applications. Ionosphere measurements of total electron content and scintillation were provided and are being assessed.
2023–2028	Commercial Purchase: Radio Occultation Data Buy 2	Ionosphere data requirements included as an option for contractors to propose. NOAA has the option to purchase low-latency total electron content and scintillation measurements in a future delivery order.

SOURCE: Office of Space Commerce (2023).

market for space weather data develops favorably, it is also possible that companies will find it profitable to include space weather instruments on their spacecraft to sell the data to the government and/or directly to space weather users. However, there are challenges regarding commercial data purchases. These include lack of existing business models for data production, availability of reasonably priced instruments that do not drive requirements on the platform, availability of real-time data acquisition, and intercalibration of the then heterogeneous instrument network.

Conclusion: In the next decade, space weather data will comprise a heterogeneous set of ground-based and space-based observations from government and commercial sources. Effective use of these data will require (1) intercalibration across the data sources, (2) quantification of their contribution to forecast and specification accuracy, and (3) methods and tools to access the distributed data sources. Efforts are needed to establish targets for data types and their spatial/temporal coverage needed to improve numerical models as well as to develop suitable data assimilation methods. Furthermore, mechanisms are needed to test new observational technologies and assess their value to the space weather enterprise.

Conclusion: NASA's Space Weather Program in the Heliophysics Division is an effective bridge between the LWS mission to focus on research that has space weather applications and NOAA's deployment of operational space weather assets. The current Space Weather Program needs to expand to include not only demonstration instruments, like the instrument on the ESA Vigil mission, but also possible stand-alone space weather demonstration missions. The current Space Weather Program budget is insufficient to accommodate this expansion.

Recommendation 3-5: As part of an overall increase in the Heliophysics Division budget, the National Aeronautics and Space Administration should grow the spaceflight element of the Space Weather Program to support larger stand-alone space weather demonstration missions with a cost cap comparable to the Heliophysics Small Explorers (i.e., approximately $150 million in fiscal year 2024).

Space weather pilot missions could include either stand-alone missions or missions of opportunity. These missions could target research observations or techniques that have either been identified as the highest-priority customer needs or as showing the most promise for improving the quality of space weather applications. Using jointly developed metrics and transition plans, the new capabilities would later be transferred from NASA to NOAA operations. In Chapter 5, a budget range is provided for this recommendation. However, this budget range is only notional, and demonstration of different technologies may require a range of mission sizes from CubeSats to much larger missions, and the operational realization of any technological advancement may not be a mission of the same size.

Space weather demonstration instrument packages could be included on commercial or NASA satellites. In either case, it is important that the space weather instrument package is considered as part of the mission design from early on, to avoid complications to the spacecraft and/or communication system design or other challenges driven by the diverging needs of the primary mission and the space weather augmentation.

Recommendation 3-6: NASA should consider space weather enhancements for all National Aeronautics and Space Administration (NASA) missions during preformulation and should look for opportunities to include space weather enhancements on other federal agency missions. Such investments could be realized through the NASA Heliophysics Space Weather Program (see Recommendation 3-5).

Space weather enhancements could include additional instruments, improvements on planned research measurements, or enhancements in data cadence, latency, or availability. Examples from the decadal survey's Panel on Space Weather and Applications assessment of mission concepts that went through the technical, risk, and cost estimate process are shown in Appendix G. For strategic missions, space weather enhancements would be evaluated during early preformulation by the science and technology definition teams. An example of a successful addition of important space weather capabilities on a NASA science mission is the Active Link for Real-Time (I-ALiRT) system on the Interstellar Mapping and Acceleration Probe spacecraft. The I-ALiRT system will provide real-time measurements from the L1 point to complement NOAA's Space Weather Follow On-Lagrange 1 (SWFO-L1) mission. Both IMAP and SWFO-L1 will be launched in 2025. Another example is the Defense Meteorological Satellite Program carried the space environment monitoring (SEM) package. With the termination of this program, SEM packages could be targeted for LEO Earth science strategic missions. Other space weather enhancement options could include targeted missions of opportunity or space weather enhancement options for the Explorer program.

Recommendation 3-7: To take advantage of new data opportunities, the National Oceanic and Atmospheric Administration (NOAA) should assess the value (e.g., through observing system experiments or observing system simulation experiments) of new data streams (e.g., from the National Aeronautics and Space Administration's research satellites or proof-of-concept studies) and incorporate those that promise to make substantial quantitative improvements into operational services. These data could also come from other ground- and space-based instruments, from U.S. agencies partnering with NOAA, commercial entities, and international partners.

3.3.6 Coordination of International Activities

The increased international interest in space weather represents an opportunity to develop partnerships to increase the availability and global coverage of ground-based and space-based observations and to accelerate the development of numerical prediction models. A good example of such collaboration is the recently signed agreement between NOAA and ESA involving ESA's Vigil mission and NOAA's L1 monitor, to be placed on complementary orbits to monitor the Sun and the solar wind. Both organizations will provide identical instruments to be included onboard both satellites, and data from the two satellites will be shared.

TABLE 3-5 Organizations Supporting Space Weather Coordination

Organization	Tasks
Committee on Space Research (COSPAR)	Advances understanding of the space environment. Develops and validates space environment models. Identifies research and observations gaps. Publishes space weather science roadmaps.
Coordination Group for Meteorological Satellites (CGMS), 2015–	Coordinates space weather activities among meteorological satellite operators. Maintains space weather operational measurements baseline. Identifies space weather needs and requirements. Develops data intercalibration procedures.
International Civil Aviation Organization (ICAO), 2019–	Promotes the safety of civil aviation. Sets standards for safety, efficiency, and environmental protection. Provides space weather advisories through a consortium of 19 countries.
International Space Environment Service (ISES)	Provides real-time forecasting and monitoring of space weather. Facilitates international communication and service coordination. Advances space weather capabilities and promotes understanding of space weather impacts.
United Nations Office for Outer Space Affairs (UNOOSA)	Coordinates member nations to promote international cooperation in space science exploration and utilization ground- and space-based data as well as technology for sustainable economic and social development.
World Meteorological Organization (WMO), 2010–	Specializes in collaboration among meteorological, hydrological, and space weather service providers. Supports a globally integrated infrastructure for the exchange of data, information, and products. Maintains observing requirements and gap analyses. Encourages research activities.

A number of international organizations are taking coordination actions regarding space weather activities (Table 3-5). The World Meteorological Organization recently established an Expert Team on Space Weather that targets to support coordination and access to globally distributed data, update observing requirements, review advances in prediction capabilities, and provide guidance on operational service delivery (WMO 2020). The Coordination Group for Meteorological Satellites is developing procedures to inter-calibrate space weather measurements from the increasing number of instruments onboard meteorological satellites. The International Civil Aviation Organization provides services for civil aviation, including advisories for communication outages, navigation errors, and enhanced radiation levels. The United Nations Office for Outer Space Affairs coordinates and promotes international cooperation in the peaceful use and exploration of space, and in the utilization of space science data and technology for sustainable economic and social development.

To promote basic and applied research in space weather, the Committee on Space Research (COSPAR) and International Living with a Star commissioned a roadmap for space weather research. Currently, the COSPAR Panel on Space Weather is organizing a broad international effort to update and transfer the roadmap to a community-driven document. The expanding interest among the research community and service providers demonstrates the opportunity to grow capabilities by coordinating effectively with global partners across the full research-to-operation spectrum.

Conclusion: U.S. participation in international coordination and collaboration activities can advance both the availability of global space weather observations and development of advanced methodologies to assimilate those measurements into the system models. Strong international frameworks both within the research community and within international organizations now exist to facilitate collaborations. It is important that in this rapidly evolving field, the United States maintains its global strategic leadership.

TABLE 3-6 Space Weather Operational Outcomes That Are Achievable in the Next Decade

Space Weather Themes	Research Focus Areas	Operational Outcomes
System of Systems: Drivers of Space Weather	Solar flares and solar energetic particles (SEPs)	>12-hour forecast for solar eruptions and >6 hours for SEPs
	Coronal mass ejections	12-hour forecast for coronal mass ejections and their magnetic fields
	Atmospheric driving	Quantify the contributions of gravity waves that may seed ionospheric irregularities that produce scintillations
Space Weather Responses of the Physical System	Low Earth orbit (LEO) neutral density	24-hour forecast of thermospheric density during geomagnetic storms for LEO spacecraft operators
	Ionospheric and magnetospheric states	Nowcast of ionospheric and magnetospheric state parameters including radiation environment, auroras, and ionospheric currents
	Reanalysis	Reanalysis capability for forecast/nowcast models to assess and validate models and forecast methods
Space Weather Impacts on Infrastructure and Human Health	Crewed mission radiation	Characterize and monitor space radiation environment for crewed and robotic missions
	Aviation radiation environment	Aviation radiation nowcasts and forecasts during large SEP events
	Spacecraft effects	Forecasts of spacecraft effects with multiday lead time
	Ionospheric high-frequency (HF) signal propagation	1-hour ionospheric HF signal propagation disturbance forecasts
	LEO satellite and debris trajectories	Model for LEO satellite and debris trajectories
	Geoelectric field	1-hour geoelectric field variation forecasts with 200 km spatial resolution for power system operators

3.4 SYNOPSIS

This chapter has mapped challenging research goals (Section 3.2) to an ambitious space weather strategy (Section 3.3), with the objective of defining a path for advancing understanding of space weather science as well as transitioning that knowledge to operations that address user needs. As space weather is driven by the highly variable output from the Sun and the complex processes that take place in the heliosystem, success is critically dependent on availability of an observational network that covers the key regions and produces data products with minimal time delay. Table 3-6 summarizes the target observational needs and operational outcomes for each research theme and focus area. These priority improvements in operational capabilities are achievable in the next decade with sufficient investment. Table 3-7 highlights some of the observational needs by research theme. Comparison with the corresponding tables in Chapter 2 reveals that while the details may vary, the basic needs are quite similar. The similarities emphasize the interlinking of the science and space weather themes, like two sides of the same coin, and highlight the opportunities for collaboration and communication between the science and operational communities.

The six-point research strategy presented in this chapter includes recommendations for actions directed toward the research community that are necessary to enable the research to operations chain.

TABLE 3-7 Space Weather Research Themes, Goals, and Observational Needs Related to Reaching the Goals

Space Weather Themes	Research Focus Areas	Observation Needs
System of Systems: Drivers of Space Weather	Solar flares and solar energetic particles (SEPs)	Simultaneous, inter-calibrated full-Sun measurements of the magnetic field and atmospheric structure, coronagraphic imaging
	Coronal mass ejections	Continuous, multiviewpoint, remote observations of coronal mass ejections; Sub-L1 upstream solar wind and interplanetary magnetic field measurements
	Atmospheric driving	Coordinated observations from heterogeneous space-based (GDC and DYNAMIC) and distributed ground-based observation networks
Space Weather Responses of the Physical System	Low Earth orbit (LEO) neutral density	Environmental measurements at LEO with good altitude and latitude coverage
	Ionospheric and magnetospheric states	Precipitating particle populations from all latitudes at LEO; polar cap potential; field-aligned currents; ionospheric irregularities; SEP access; and energetic particle and plasma transport, acceleration, and loss
	Reanalysis	Repositories of state space models of the magnetosphere and the ionosphere–thermosphere–mesosphere system, spanning many solar cycles
Space Weather Impacts on Infrastructure and Human Health	Crewed mission radiation	Continuous monitoring of the radiation environment from the LEO to lunar orbit; for Martian missions for entire inner heliosphere
	Aviation radiation environment	SEP timing, intensity, and spectra
	Spacecraft effects	Energetic particle environment in the magnetosphere
	Ionospheric high-frequency signal propagation	Ground-based coverage in key geographic areas, satellite-based radio occultation
	LEO satellite and debris trajectories	Gas-surface interactions and forcing at different LEO altitudes and latitudes
	Geoelectric field	Geomagnetic field variations at high spatial and temporal resolution

Research advances that occur over the next decade will be an essential element of the recommended improvements to the R2O2R cycle involving government agencies, academia, private industry, and international partners. Although multiple government agencies have space weather efforts (including NASA, NSF, NOAA, the Department of Energy, the U.S. Geological Survey, and the U.S. Air Force), these efforts are not yet well coordinated.

Research efforts are typically not targeted to specific protective actions, and research advances often are not directly usable as improved space weather information. For example, NASA's Van Allen Probes mission obtained valuable measurements throughout the inner magnetosphere where satellites are vulnerable to radiation impacts. However, NOAA did not have a physics-based numerical prediction model that could use these data while they were available. Despite numerous scientific discoveries from this mission, the knowledge gained has not yet resulted in improved services. Similarly, with GDC and DYNAMIC expected to obtain comprehensive measurements of Earth's ionosphere and upper atmosphere, NOAA currently does not have a numerical model that will efficiently ingest these data to improve the nation's satellite collision avoidance and space traffic coordination capabilities.

These issues can be resolved in the next decade if existing interagency agreements, already approved by the government agencies, are fully implemented. Following the direction of the PROSWIFT Act, the framework agreement, and the quad-agency MoA, the multiagency executive board and steering committee will work within the national effort to ensure that agency efforts are focused and that they achieve measurable results. The research community will know what advances are needed. And when advances are made, they will be implemented in operational services with quantifiable value.

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4

Toward a Thriving Solar and Space Physics Community

The decadal themes presented in Chapters 2 and 3 encompass basic research and space weather focus areas for which significant progress can be made with adequate investment. These themes range from understanding the underlying physical processes that drive the Sun–Earth environment, venturing into new environments to test theories and make new discoveries, and advancing space weather research, from physical drivers to effects on society. The starting point for realizing these scientific advancements is the health and vitality of the solar and space physics community. Although there are issues of diversity across all science, technology, engineering, and mathematics (STEM) fields, this report focuses on the practicalities of addressing those issues for the solar and space physics community. Adequate investment is required to ensure a productive and diverse workforce that can realize the vision for solar and space physics.

Since 2020 several National Academies of Sciences, Engineering, and Medicine studies and reports have evaluated the space sciences profession, particularly focusing on the Science Mission Directorate (SMD) of the National Aeronautics and Space Administration (NASA). Two National Academies reports addressed the profession: *Advancing Diversity, Equity, Inclusion, and Accessibility in the Leadership of Competed Space Missions* (NASEM 2022a; hereafter, the *Advancing DEIA* report) considered the career pathways and institutional process that produce mission leaders, and *Foundations of a Healthy and Vital Research Community for NASA Science* (NASEM 2022b; hereafter, the *Foundations* report) considered the scientific research community within SMD, converging on the following six attributes of community health and vitality:

- Clarity of science for efficient research and public support, using clear scientific questions to guide research solicitations;
- A representative workforce of U.S. society in general, demonstrating diversity, inclusion, equity, and competence across a broad range of characteristics;
- Sustaining a diverse science enterprise through outreach, acceptance, and development;
- Adequate funding;
- Resilience to emerging challenges; and
- Community standards of conduct.

This decadal survey includes the work of the Panel on the State of the Profession, a diverse group of scientists from a range of backgrounds and career levels, including social scientists. The panel report (see Appendix F) identifies barriers and suggests solutions for the advancement of a healthy and sustainable solar and space physics community in the next decade.

Guided by that panel report, the 450 white papers submitted by the solar and space physics community to this decadal survey (referred to in this report as community input papers), and the *Advancing DEIA* and *Foundations* reports, the committee identified focus areas that fall under four themes: see Figure 4-1. Targeted investments in each of these focus areas will invigorate the state of the profession over the next decade.

An important concept throughout this report is DEIA+, which is the acronym for diversity, equity, inclusion, and accessibility, a phrase used to define policies, behaviors, and beliefs that support the opportunity for all to

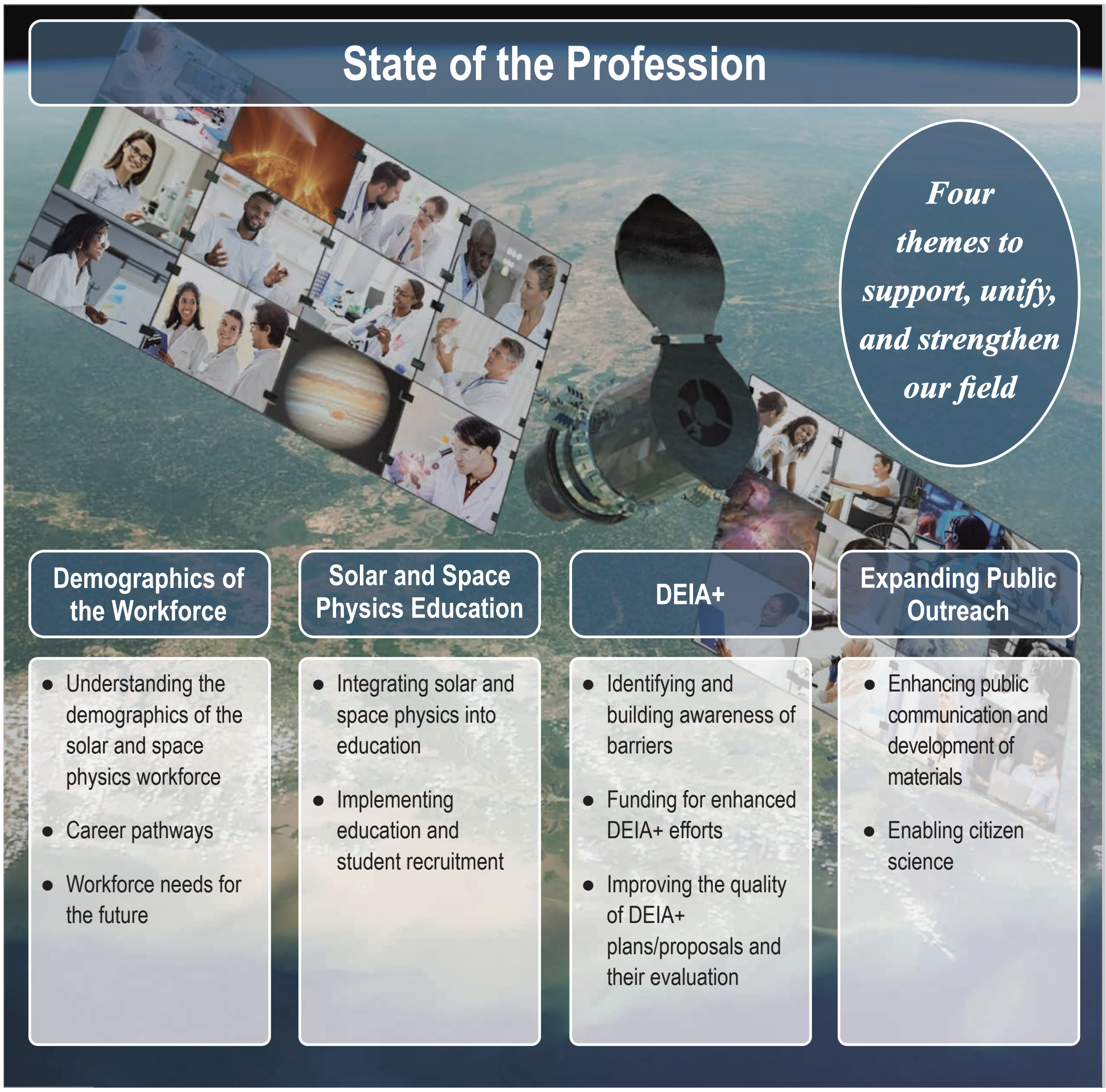

FIGURE 4-1 State of the Profession themes and focus areas. Targeted investments in each of these focus areas will invigorate the state of the profession over the next decade.
NOTE: DEIA+, diversity, equity, inclusion, and accessibility, as well as anti-racism, accountability, and justice.
SOURCE: For source information on the images in this figure, see the note at the end of the chapter.

participate and develop within a community. The "+" includes anti-racism, accountability, and justice. Additional helpful definitions are included in Appendix F and in NASEM (2022a).

The first section below provides an overview of the solar and space physics community and discusses opportunities and challenges associated with a field that is broad and draws on technical expertise from a wide range of disciplines.[1] The subsequent four sections present the current demographics and desired future characteristics of the field: a diverse workforce that engages in interdisciplinary collaborations and makes advances in scientific research and practical applications. The first covers the importance of understanding the demographics of the field and associated challenges (Theme 1), along with recommendations for ensuring recruitment and retention of a diverse workforce with a broad range of skills and expertise. This will require better incorporation of solar and space physics into mainstream STEM education (Theme 2); better support for DEIA+, (Theme 3); and enhanced engagement with the general public to generate excitement about the field (Theme 4).

4.1 THE SOLAR AND SPACE PHYSICS COMMUNITY

The solar and space physics discipline comprises the study of the space environment, including the coupled Sun and heliosphere, as well as the magnetospheres, ionospheres, and neutral upper atmospheres of Earth and other planets. The solar and space physics community consists of the interconnected systems of individuals, departments, and institutions that are associated with a variety of funders, professional societies, and societal needs.

Currently, solar and space physics is one of the umbrella terms that encompass the different components of the discipline. Within NASA's SMD, the term "heliophysics" is used to clearly distinguish it from Earth sciences, astrophysics, and planetary science disciplines. Understanding the people who make up the current solar and space physics community and the ability to study trends to assess the health and vitality of the discipline continues to be difficult due to the lack of a standard name for the discipline within different organizations. Those names include:

- Solar and space physics (the National Academies),
- Heliophysics (NASA), Geospace Sciences and Solar Physics (in separate divisions of the National Science Foundation [NSF]),
- Space Weather (the National Oceanic and Atmospheric Administration [NOAA], the U.S. Air Force, and the American Meteorological Society),
- Space Physics and Aeronomy (SPA) (American Geophysical Union [AGU]),
- Solar Physics (Solar Physics Division [SPD] of the American Astronomical Society [AAS]), and
- Various other permutations within universities.

The lack of a common name was raised in the 2013 solar and space physics decadal survey report (NRC 2013; hereafter, 2013 decadal survey) and continues to hinder the community's ability to articulate its science broadly to the public and invested parties, as well as assess the state of the profession.

To elaborate, this lack of a unique identity raises three significant challenges for the profession:

1. *Data gathering:* To understand the profession and its evolution, demographic information is critical. Specifically, tracking this information can help to ensure that a strong future workforce is recruited, receives the right training, and is healthy and sustainable. In order to consistently collect accurate demographics data, a common label is needed for the field.

[1] From NASEM (2022a): "Several studies have demonstrated that multiple forms of diversity are beneficial to the creativity, innovation, and impact of science teams (Hong and Campbell et al. 2013; Freeman and Huang 2014a,b). Although social scientists continue to try to understand how specific forms of diversity (e.g., racial/ethnic, gender, career stage diversity) relate to various aspects of team performance, it is generally understood that, when engaged productively in an inclusive environment, diverse perspectives, experiences, and backgrounds can strengthen teams and lead to better science (Sommers 2006; Diaz-Garcia et al. 2013; 2017). Accordingly, the National Aeronautics and Space Administration's (NASA's) Vision for Scientific Excellence notes, 'diversity is a key driver of innovation and more diverse organizations are more innovative. . . . NASA believes in the importance of diverse and inclusive teams to tackle strategic problems and maximize scientific return' (NASA 2020b)."

2. *Recruitment:* To recruit a diverse workforce (on many dimensions), better exposure to the field of solar and space physics is needed in schools and colleges; every science textbook could describe the space environment and mention the Sun, the magnetic fields of Earth, and planets.
3. *Public outreach:* While solar and space physics science is exciting and has important ramifications for life and society on Earth as well as in space, public awareness of the subject is lacking (while there is better awareness of astronomy). The public does not associate the subject with an independent scientific field or a professional community. Better communication, including a wider variety of appealing graphics and animations, will help to raise public awareness of the valuable science of solar and space physics.

Conclusion: A common name for the field that can be broadly called solar and space physics would improve efforts in data gathering, recruitment, education, and public outreach.

There are challenges to deciding on a common name that are rooted in the different orientations of U.S. agencies engaged in solar and space physics research and operations, and even among different divisions within an agency. All of the names considered by the decadal committee introduced a bias toward particular subdisciplines in the field. A solar and space physics consortium (discussed below) that solicits input from the community could be an important mechanism for addressing this issue. In this report, the broad term "solar and space physics" is used.

4.2 THEME 1—DEMOGRAPHICS OF THE WORKFORCE

The solar and space physics profession comprises a myriad of subdisciplines, existing at the intersections among plasma physics, practicalities of the space environment, engineering, Earth science, planetary science, and astronomy. The emerging subfield of space weather encompasses not just academic science, but also applied sciences and commercial endeavors. In addition to foundational scientific knowledge, advancements in basic research and space weather require expertise in computational modeling, engineering, applied mathematics, data science, and prediction methodologies, as well as management, communications, and operations.

Historically, the "workforce" has referred to potential principal investigators (PIs) or their students who proposed studies related to solar and space physics to agency funders. In reality, the workforce includes academics, research scientists (including those at government labs, universities, and federally funded research and development centers, and in industry and private institutions), postdoctoral researchers, and graduate and undergraduate students working in subfields in solar and space physics. Moreover, consideration of the solar and space physics workforce has not historically recognized the engineers, computer scientists, management personnel, and others who support and enable the science and space weather applications. Additionally, the field is expanding into new areas, such as comparative studies of stars and planetary systems, that require a broad range of expertise and increased collaboration.

Conclusion: As the field of solar and space physics expands from pure academics to include more applied areas, the understanding of the workforce—both in description and by numbers—needs to evolve, for example, to include how many soft-money researchers, early career scientists, civil servants, data analysts, and tenured faculty are working in the field.

4.2.1 Understanding the Demographics

Preparation for the 2013 decadal survey included a demographics survey, carried out in 2011 (White et al. 2011; hereafter, the "2011 workforce survey"). For the current decadal survey, there was no specific workforce survey carried out by the agencies, despite a survey having been recommended by the midterm assessment report on progress toward implementation of the 2013 decadal survey's recommendations (NASEM 2020b). The report of the Panel on the State of the Profession includes demographic data from the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) program and Geospace Environment Modeling (GEM) workshops, as well as from analysis of proposals submitted to NSF and NASA. Demographics of the overall space sciences workforce are also presented in recent NASA and National Academies reports (NASA 2023b; NASEM 2022a,b) and reviewed in Bagenal (2023).

Despite incomplete data, the subsections below review the available demographic data as sliced from a variety of viewpoints: the total size of the workforce; the statistical significance of surveys; gender, race, ethnicity, and national origin; and evolution over time. It is important to note that the terminology used in surveys to describe gender, race, and ethnicity has changed over the past decade. In this report, gender is described as man or woman except where the original survey used male or female. A continuing challenge is the lack of comprehensive and complete demographic data.

Size of the Solar and Space Physics Workforce

The total size of the U.S. workforce in solar and space physics is difficult to quantify. The 2011 workforce survey request was sent to 2,560 unique email addresses (from the AGU Space Physics and Aeronomy Section SPA), the AAS SPD, the Space Weather Week attendee lists, and the NSF list of PIs). If the 8 percent of respondents who were students are removed, that leaves an estimated 2,355 PhD scientists in the solar and space physics workforce in 2011. Without a complete repeat survey, it is hard to accurately determine changes to this number over the past decade. Membership in the largest professional organization, AGU SPA (about 63 percent of whom reside within the United States), has fluctuated by about 10 percent from 2013 to 2023. As the solar and space physics field expands, particularly into such applications as space weather, broader groups in the profession need to be carefully surveyed.

One way to quantify the workforce is to look at the personal profiles submitted through the NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES), an online proposal tool. In 2023, NASA's Office of the Chief Scientist provided data on the number of unique names attached to proposals submitted by PIs and co-investigators (Co-Is) at U.S. institutions. These data did not include proposals for student fellowships, early career grants, or researchers directly funded by missions. (Data on graduate students and early career scientists have been gathered by organizations such as CEDAR; GEM; and the Solar, Heliospheric, and INterplanetary Environment [SHINE] program).

Figure 4-2 shows the total number of unique names of PIs and Co-Is for the different divisions in SMD between 2011 and 2021. The data for the Heliophysics Division shows a flat profile of almost 1,000 people who submitted proposals each year, about 39 percent of the 2,355 U.S. PhD scientists in the 2011 workforce survey.

Table 4-1 compares the populations from the 2011 workforce survey and the 2023 *NASA Researcher Demographics Report* (NASA 2023b). Note that in the 2011 workforce survey, 66 percent of respondents said they sought funding outside their employment institution, 74 percent from NASA, and 46 percent from NSF.

A rough estimate of growth in the field can be obtained by counting job advertisements. As reported by the Panel on the State of the Profession, Moldwin et al. (2016) compiled the number of job advertisements posted in the AGU SPA and the AAS SPD newsletters for postdoctoral, research scientist, and faculty positions, as well as the number of new PhDs granted each year in solar and space physics from North American universities. In 2010 (just into the recession of 2008–2009), global postdoc, research scientist, and faculty job ads fell to the lowest levels in the decade (and ads for faculty positions fell to just 7 from the typical 15–25 per year from 2001 to 2009). Since 2016, the number of ads in all three positions has increased, reaching an all-time high (Moldwin 2023). However, absent a quantitative census to determine the size of the field, it is impossible to say whether these increases are sufficient to keep pace with expansion of the discipline into emerging areas. Additionally, workforce increases are difficult to compare with overall funding increases due to the complexity of defining the field in terms of both people and fractions of agency budgets.

Statistical Issues with "Prefer Not to Answer"

Most surveys have an option to not answer questions about one's personal information (e.g., age, gender, race, ethnicity). Often 15–20 percent of people respond, "prefer not to answer" (PNA), probably for a variety

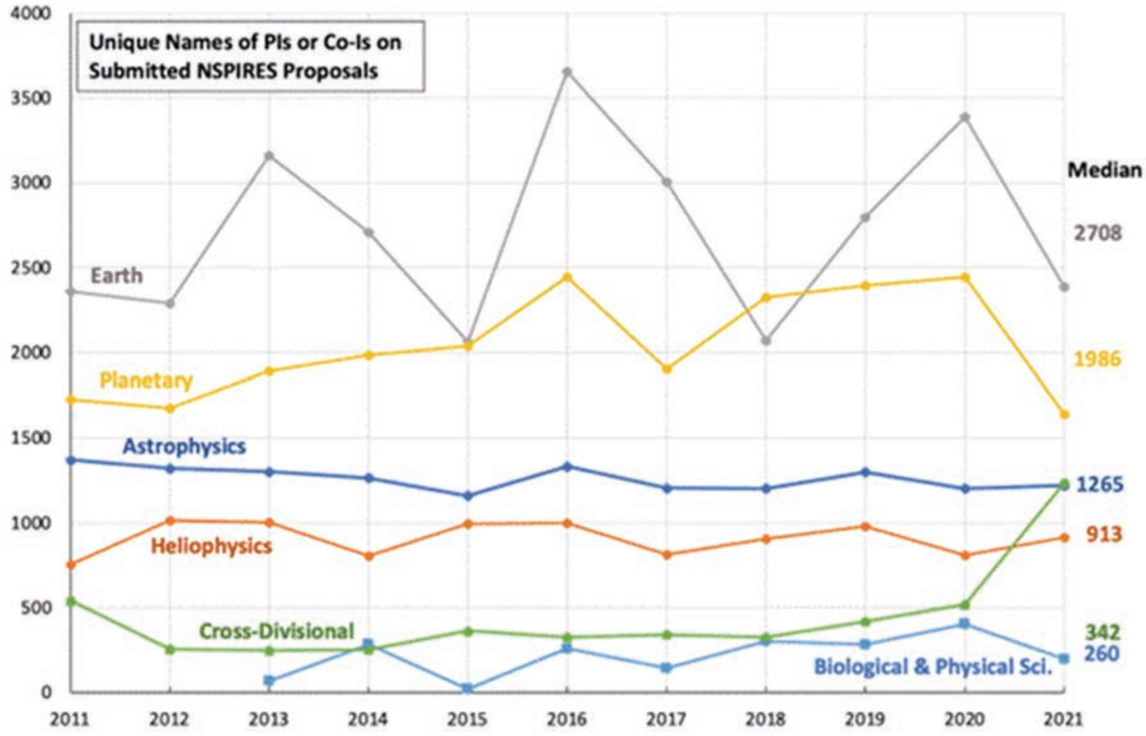

FIGURE 4-2 Number of unique names of PIs or Co-Is at U.S. institutions who submitted proposals through NASA's NSPIRES to all disciplines.
NOTES: Student fellowships and early career awards were not included. Co-I, co-investigator; NSPIRES, NASA Solicitation and Proposal Integrated Review and Evaluation System; PI, principal investigator.
SOURCE: Based on data from NTRS (2023).

TABLE 4-1 Comparison of Survey and NSPIRES Populations

Survey	Who Was Polled	Total[a]	NSPIRES[b]	NSPIRES/Total (%)
Astronomy and Astrophysics 2018	AAS[c]	4,127	1,265	31
Planetary Sciences 2020	AAS Division for Planetary Sciences, Lunar and Planetary Science Conference, Geological Society of America	4,568	1,986	43
Solar, Space, and Upper Atmosphere Physicists	AGU Space Physics and Aeronomy, AAS Solar Physics Division, Space Weather Week, attendees, NSF PIs	2,344	913	39

[a] Total membership in U.S. with a PhD with unique names.
[b] Median number of unique names of PIs and co-Is submitting to NASA's NSPIRES system 2011–2021.
[c] Sample of 3,354 members polled; 26 percent of respondents were students.
NOTES: AAS, American Astronomical Society; AGU, American Geophysical Union; NSF, National Science Foundation; NSPIRES, NASA Solicitation and Proposal Integrated Review and Evaluation System; PI, principal investigator.
SOURCES: Based on data from Pold and Ivie (2018); Porter et al. (2020); White et al. (2011).

of reasons (there are anecdotal explanations but no studies of any systemic causes), which has a significant effect on the statistical validity of the results. The percentage of PNAs has decreased from 2014 to 2020 in the NASA NSPIRES database (NASA 2023b) and the proposal success rates of PNAs are similar for those who provide personal information. In contrast, a study of proposals submitted to the NSF Directorate for Geosciences (GEO) (before 2019) shows lower acceptance rates of proposals from applicants in historically minoritized communities and a distinct *decline* in percentage of proposers who provide demographic information (Chen et al. 2022). To better capture trends for the solar and space physics community, such a study needs to be carried out for the NSF Division of Atmospheric and Geospace Sciences, which accounts for a small fraction of scientists in GEO.

Gender

Until recently, only a binary choice of gender (male/female or man/woman) was available on surveys. More recent surveys have expanded the choice to include nonbinary, but the statistical significance of such data is strongly affected by many PNAs. From the Panel on the State of the Profession (in Appendix F):

> From 2016 to 2021 the SPA "primary" AGU membership (3,600) and total (5,600) membership (AGU allows members to indicate "primary" sections and multiple other section affiliations such as Planetary or Atmospheric or Education) was fairly steady. The AGU SPA primary section affiliation membership in 2021 was 23.9 percent women compared to 33 percent of all AGU members, 35 percent for Planetary Scientists (Bagenal 2023) and the 17 percent representation by women found in the previous decadal survey snapshot taken in 2013. In 2017, 31 percent of American Astronomical Society members were women (Pold and Ivie 2018). Taken at face value, the solar and space physics community has made progress in representation by women (17 to 24 percent) but is still underrepresented in comparison to the broader Earth and Space Science Community and to other space science disciplines.

Figure 4-3 shows that the gender of proposers to Heliophysics grant opportunities through the NASA NSPIRES online system did not change substantially between 2014 and 2020; the percentage of NASA proposals submitted by applicants identifying as women has varied between 16 and 21 percent, and those identifying as men varied between 67 and 71 percent. Over the same period, the percentage of PNAs ranged between 11 and 16 percent. Such large total numbers of PNAs suggests that the changes in submissions by women may not be statistically significant.

> *Conclusion: To accurately assess the demographics of the solar and space physics community, professional organizations and funding agencies need to communicate the importance of providing one's demographic information when submitting proposals. It needs to be clear to proposers that this demographic information is not available to reviewers. Regular reminders to update one's personal profile could be sent out to the community; ideally, such reminders would not be connected with proposal deadlines.*

Race, Ethnicity, and National Origin

Survey questions about race and ethnicity have evolved from a choice of White vs. non-White to a range of categories (e.g., Black/African American, Latinx/Hispanic, and American Indian/Alaska Native/Pacific Islander). Total numbers of racially minoritized individuals in the field remain small, sometimes too small to be reported (<1 percent). The CEDAR workshop data (2021–2022) show student and early career populations are considerably more diverse than the senior scientists (see Appendix F, Figures F-3 to F-6).

As shown in Figure 4-4, the demographics of the solar and space physics workforce are largely White men. The percentage of women is lower for heliophysics than the other areas of space science, but that may be partly related to the fact that the demographic data are from a survey carried out several years earlier than for the other fields. The stark lack of non-White populations is clear across all fields. Note that the data for heliophysics in Figure 4-4 came from the 2011 survey; a modern survey may show increased diversity.

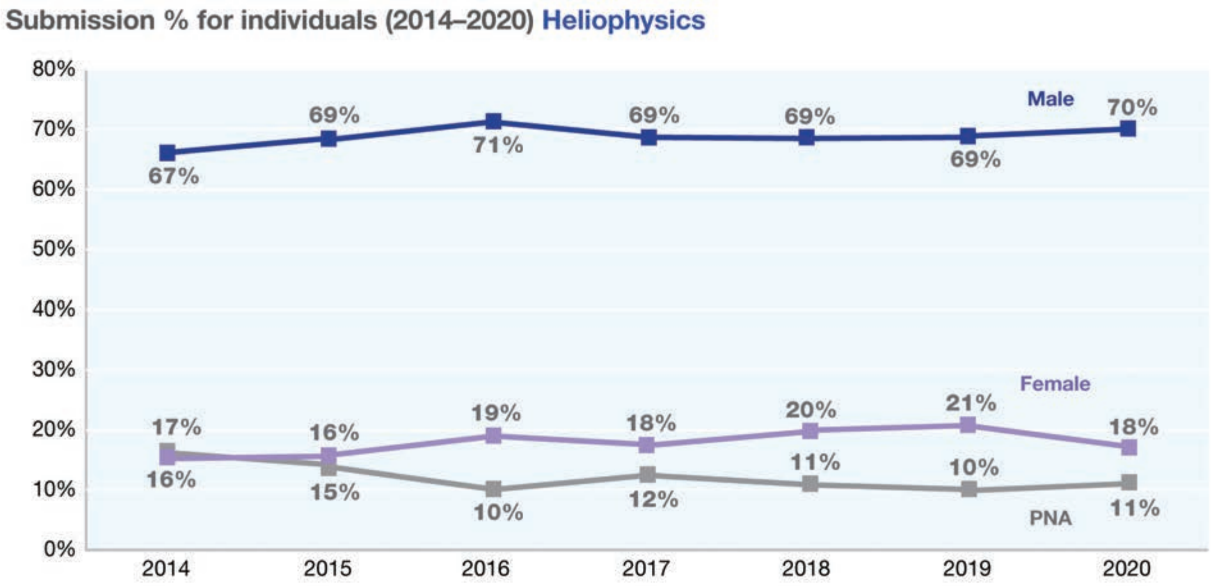

FIGURE 4-3 Gender identity demographics of the most recent survey of heliophysics researchers submitting proposals to NASA, 2014–2020.
NOTE: PNA, prefer not to answer.
SOURCE: NTRS (2023).

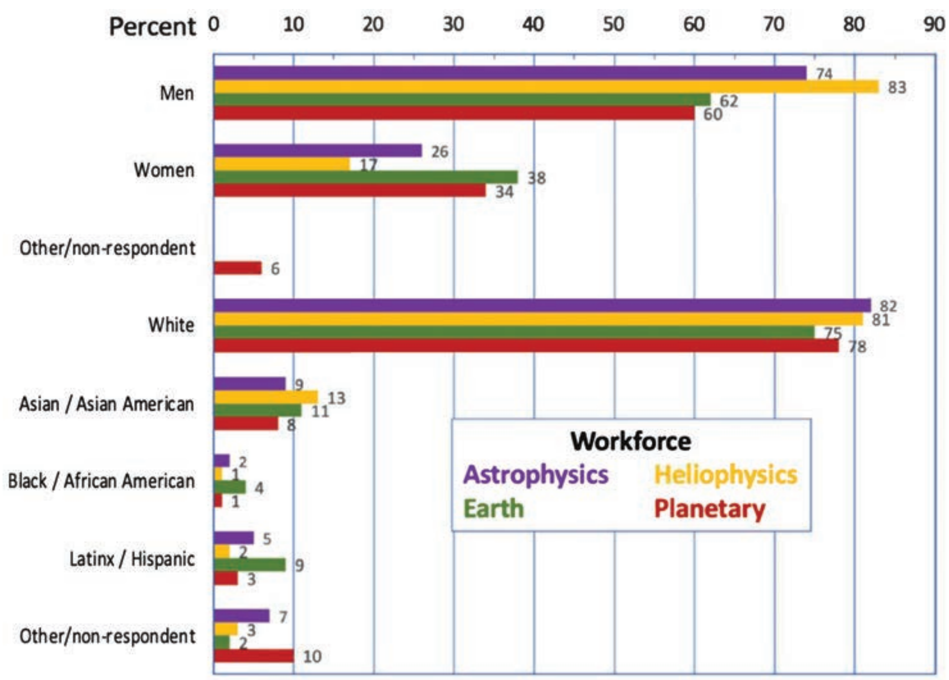

FIGURE 4-4 Demographics of the space science research workforce as represented by PhD scientists working in the United States.
NOTE: The demographic data were derived from workforce surveys: astrophysics in 2018, Earth sciences in 2018, solar and space physics/heliophysics in 2011, and planetary science in 2020.
SOURCES: Based on data from AIP Statistical Research Center (2018); Bernard and Cooperdock (2018); NASEM (2022a); NCSES (2023); Pold and Ivie (2018); Porter and Ivie (2019); Porter et al. (2020); White et al. (2011).

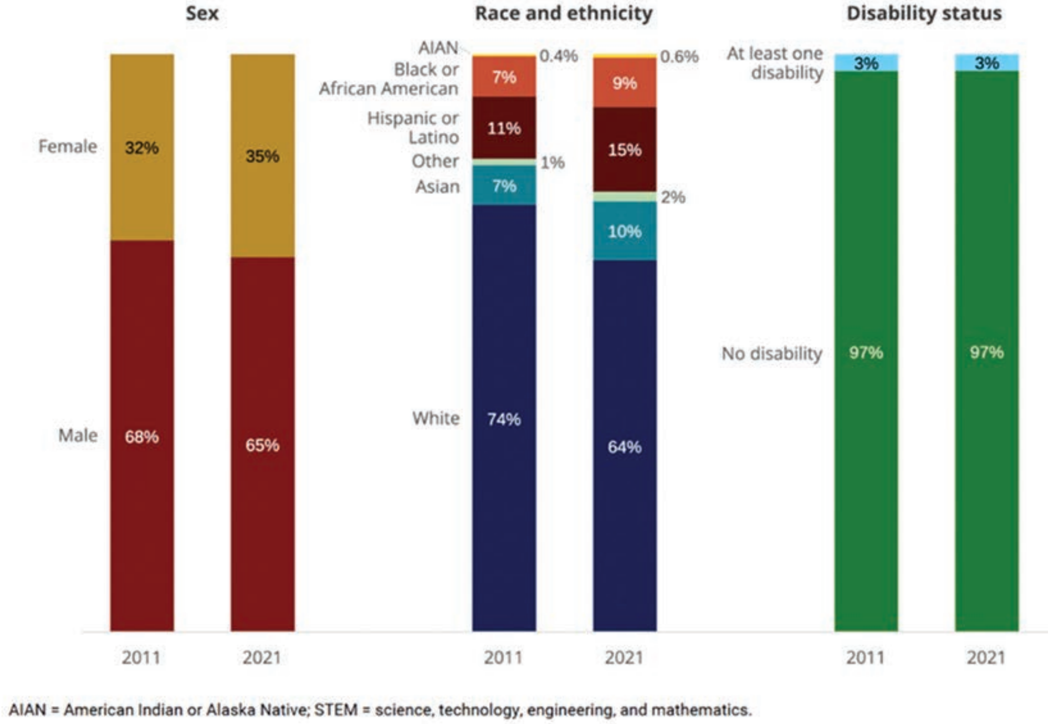

FIGURE 4-5 Characteristics of the STEM workforce ages 18–74: 2011 and 2021.
SOURCE: NCSES (2023).

Evolution with Time

Looking across the national workforce in all STEM fields, NSF (2023) showed significant diversification of the workforce from 2011 to 2021, though access for those with disabilities remains very limited: see Figure 4-5.

Specifically looking at the solar and space physics community in Figure 4-6, the NASA NSPIRES data on the demographics of proposing PIs and co-Is to the Heliophysics Division show an increasing percentage of proposals

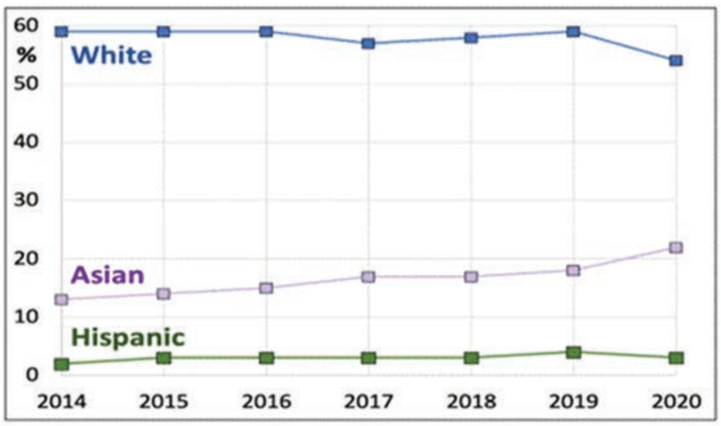

FIGURE 4-6 Race, ethnicity, national origin demographics of PIs and Co-Is of proposal submissions to the Heliophysics Division through NSPIRES.
NOTES: Data for Black/African American, American Indian/Alaska Native, Native Hawaiian and other Pacific Islander, and multiracial researchers remain below the 1 percent level (too low to be included in the figure). These terms are used by NASA in accordance with guidance from the Equal Employment Opportunity Commission. Co-I, co-investigator; NSPIRES, NASA Solicitation and Proposal Integrated Review and Evaluation System; PI, principal investigator.
SOURCE: NASA (2023b).

submitted by Asian researchers with little change for Hispanic researchers, while submissions by Black/African American, American Indian/Alaska Native, Native Hawaiian and other Pacific Islander, and multiracial researchers remain below the 1 percent level (too low to be included in Figure 4-6). According to the 2023 census results, the U.S. population demographic is 58 percent white (not including Hispanic or Latino), 20 percent Hispanic or Latino, 14 percent African American, and 6 percent Asian. While Figure 4-5 shows that race and ethnicity percentages in STEM are trending to be much more aligned with the population, Figure 4-4 shows that the space sciences are unfortunately lagging behind.

Solutions: The Need for Better Data

Performing community surveys is a difficult task, but it is worth the effort. The information provided by demographic surveys is crucial for informing agencies about the success of initiatives to further DEIA+ goals. The lack of reliable demographic data has been discussed in other reports, with several variations of suggested solutions (NASEM 2022a,b, 2023a,b). For example, the *Foundations* report (NASEM 2022b) recommended that funding be provided to one or more umbrella organizations (such as the American Institute of Physics [AIP]) to conduct longitudinal studies of demographics in solar and space physics. With the currently available data, it is not possible to discuss intersectionality—how different social categories such as race and gender interact with each other to shape experiences and opportunities—due to small sample numbers of some demographics. In the future, if appropriate data are available, an intersectional view would be highly beneficial.

Conclusion: To address issues related to the state of the profession, the solar and space physics community needs to understand the demographics of the past, current, and potential future workforce. Because the solar and space physics workforce spans a broad range of disciplines, gathering the requisite data is complicated.

Conclusion: Demographics of proposal success rates need to be transparently evaluated to assess progress at different agencies, including NSF and NASA.

Recommendation 4-1: The National Aeronautics and Space Administration, the National Science Foundation, and the National Oceanic and Atmospheric Administration should fund either a professional organization (or group of organizations) or a team of researchers to develop a method to systematically gather demographic information of the current workforce in solar and space physics and obtain past demographic information (where possible) to assess demographic changes. A primary objective of this effort would be to initiate a sustainable structure for continuous, longitudinal data gathering, including at the level of undergraduate majors and conference attendees, to assess the potential future workforce and determine if the pool is sufficient to meet the needs of solar and space physics. Initial results should be provided in advance of the start of the midterm assessment of the present decadal survey.

Because the solar and space physics workforce is spread across multiple professional organizations, the data gathering should be coordinated by an umbrella organization or team of researchers in the form of a solar and space physics consortium. Demographic data-gathering surveys need to involve social science expertise, specifically, demographers and survey researchers, and they need to draw from previous surveys, such as the NSF Survey of Earned Doctorates (NSF 2023). To assist in both the immediate need for information and the desire to have a sustained, long-term tracking of data in place, it is recommended that the agencies aspire to a short-term and a long-term goal.

The short-term goal is to conduct a survey immediately that is cross-cutting and comprehensive to understand the current state of the demographics in the profession, including a survey of academic institutions that are producing bachelor of science (BS), master's, and PhD graduates who may end up in the field. This may be undertaken by an umbrella organization or by a team of researchers in solar and space physics who apply for funding in response to a solicitation. The results of this survey would be most useful if disseminated publicly prior to the midterm assessment.

The long-term goal is to establish a framework for longevity to provide longitudinal views of the evolving workforce. This phase will likely require an umbrella organization in collaboration with the various agencies. It could be one part of a solar and space physics consortium that has broader purposes such as outreach, education, and advocacy. It is vital that survey experts are committed to conducting thorough solar and space physics community surveys, analyzing the outcome, and making the outcomes publicly available on a regular basis.

To expeditiously accomplish the above short- and long-term goals, a committee could be convened, consisting of representatives from the relevant agencies, to decide the best course of action in each case and determine the funding structure.

4.2.2 Career Pathways

NASA, NSF, and NOAA support of a solar and space physics consortium would enable the balance between the number of PhDs, postdocs, and permanent positions to be assessed, along with the balance between soft-money and hard-money permanent positions. Sharing the results of such regular assessments will inform those considering heliophysics career paths and help the community address imbalances. The potential roles of a solar and space physics consortium are detailed in several other recommendations in this chapter.

Figure 4-7 presents a conception of career pathways in solar and space physics in the broader context of STEM careers. The traditional assumption is that STEM careers are a single pipeline that flows from undergraduate training to a graduate degree and into the profession. In reality, there are multiple career paths that can bring people

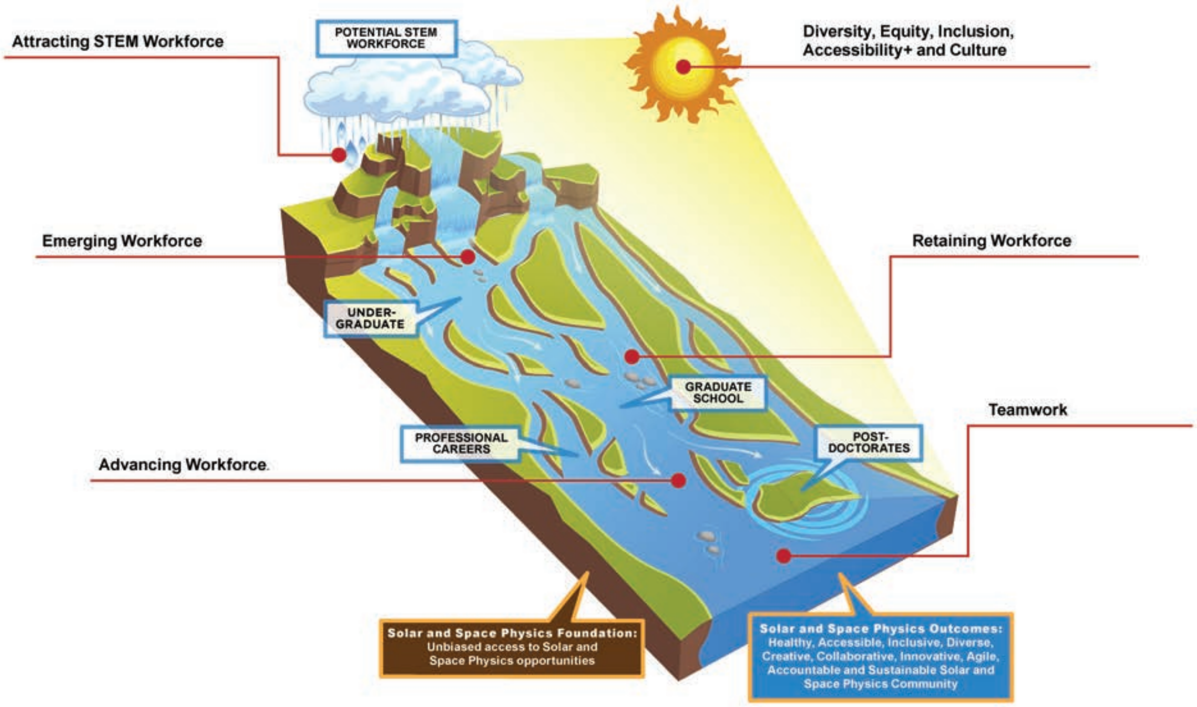

FIGURE 4-7 Braided stream pathways of careers in solar and space physics.
NOTES: See Appendix F for a more detailed version of this figure that includes specific suggestions of how to improve and expand the pathways to a successful career. DEIA+, diversity, equity, inclusion, and accessibility, as well as anti-racism, accountability, and justice; STEM, science, technology, engineering, and mathematics.
SOURCE: Adapted from R.L. Batchelor, H. Ali, K.G. Gardner-Vandy, A.U. Gold, J.A. MacKinnon and P.M. Asher. 2021. "Reimagining STEM Workforce Development as a Braided River." *Eos* 102. https://doi.org/10.1029/2021EO157277. CC BY-NC-ND 3.0.

into—and sometimes out of—their solar and space physics careers, as depicted in Figure 4-7. To understand the limited diversity of the workforce, it is necessary to explore the various pathways people follow throughout their careers. What are the entry points and at what stages do people leave the field?

4.2.2.1 Undergraduate Programs

The 2011 workforce survey showed that most (62 percent) of the solar and space physics workforce obtained bachelor's degrees in physics. The AIP regularly gathers and publishes data from physics departments across the United States. Figure 4-8 shows the change in gender representation in physics careers at universities, with a major dropoff in the percentage of women participating in physics between high school and completion of a bachelor's degree. Multiple studies over the past 3 decades show this major decline in participation of women. More recent studies show racially and ethnically minoritized individuals in STEM drop out in the first couple of years of college (Seymour and Hewitt 1997; Seymour and Hunter 2019). The percentage of racially minoritized groups along such an academic career path is even smaller, with similar dropoff between the high school and college levels.

Addressing the major drop in participation in STEM fields between high school and college requires attention at both levels. While high school education is controlled locally, there are ways for science outreach activities—particularly involving the excitement of space exploration—that could have significant impact (discussed further below). There are many suggestions for addressing the high dropout rate of historically excluded populations from STEM fields in the early years at college, many of which need to be addressed locally at the university or departmental level. Those suggestions include improving the quality of teaching of freshman calculus and physics courses and including working with science education researchers. However, there are important contributions that can be made at the national level, specifically, the development and funding of Research Experiences for Undergraduates (REU) and Bridge programs, as well as supplementing research grants to include support of student involvement in research through mentorships and scholarships. In addition, the AIP runs a national Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP) to increase undergraduate participation and degree completion (AIP 2023c).

With the solar and space physics workforce evolving to include more applied fields, it is important that such internship programs for undergraduates are broadly advertised to departments beyond physics, including engineering, computer science, data science, Earth sciences, planetary science, and astrophysical science. These departments

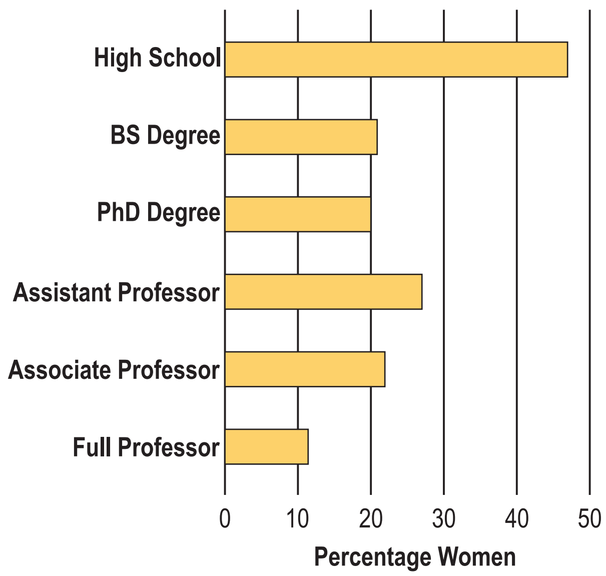

FIGURE 4-8 Percentage of women participating in physics at various academic stages between high school and bachelor's degrees.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Based on data from AIP (2022, 2023a,b).

have students who might be attracted by a positive research experience and thus consider a career in solar and space physics (see further discussion below).

Graduate Programs

It is difficult to assess the workforce in the field of solar and space physics because the disciplines of degrees held by researchers are evolving, spreading from mainly physics to other fields, such as atmospheric science, geosciences, computer science, aerospace engineering, and an increasing number of programs focused on solar and space physics. The 2011 workforce survey shows that the percentage of the solar and space physics workforce with doctorates in physics has decreased from 40 percent (for 1999 and earlier PhDs) to 27 percent (for 2000 and later PhDs). As the number of departments offering graduate programs in solar and space physics has increased, an increasing percentage of solar and space physics researchers obtain their PhDs in the specialized fields of space physics and solar physics. How such PhDs are counted by the AIP surveys is not clear.

Figure 4-9 shows the demographics of physics PhD recipients. While the total numbers have fluctuated and risen overall for the past 30 years, the percentage representations have not changed much. The current gender and race and ethnicity distributions in Figure 4-9 are similar to those across the heliophysics workforce shown in the demographics statistics presented above. Figure 4-9 shows that although the total number of PhDs in physics has increased by 22 percent in 2010–2020, the percentage awarded to men and women has remained the same at 80 percent and 20 percent, respectively. The percentage of PhDs in physics awarded to U.S. and non-U.S. citizens has remained roughly the same (54 percent and 46 percent, respectively as of 2019). The percentage of PhDs awarded to Latinx/Hispanic students has increased steadily to 2 percent. The percentage of Black/African Americans remains well below the 1 percent level. Both of these percentages remain considerably below the general STEM workforce shown in Figure 4-5 (15 percent and 9 percent, respectively, in 2021).

There are several studies examining how graduate-level education could be improved and how to diversify the student population. For example, Posselt (2020) contains a succinct list of actions related to recruitment, admissions, mentoring, support, and creating conditions conducive to equity in graduate programs.

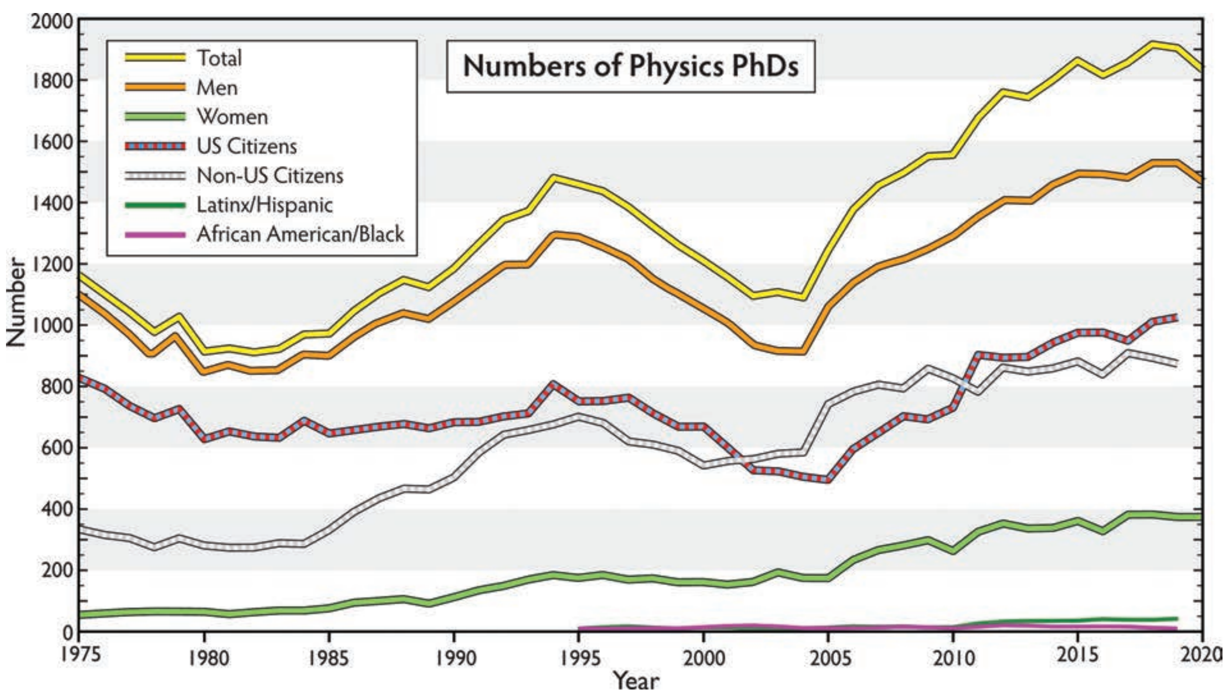

FIGURE 4-9 Trends in physics disaggregated by gender and citizenship status as well as race and ethnicity.
SOURCES: Based on data from AIP (2022); Mulvey et al. (2021); Nicolson and Mulvey (2022).

International Workforce

It is important to note the continued presence of non-U.S. PhD students. As noted in the *Advancing DEIA* report (NASEM 2022a):

> Data from the American Institute of Physics show that for the past ~30 years, about half of the PhDs in physics were awarded by U.S. universities to foreign-born scientists. Many such students stay in the United States pursuing research careers. Additionally, non-U.S. scientists immigrate as postdoctoral researchers. Thus, a significant fraction of the space science workforce are foreign-born scientists and engineers who make substantial contributions to NASA's space missions. They also contribute to the diversity of the space sciences workforce, with respect to gender and race/ethnicity. (p. 13)

Although this report focused on NASA missions, the same issues apply across the solar and space physics workforce.

A 2020 report from the American Academy of Arts and Sciences, *The Perils of Complacency: America at a Tipping Point in Science and Engineering*, addressed this issue. One of their key messages is:

> The United States is in severe danger of no longer being the premier destination for science and engineering talent. An increasingly unwelcome environment for foreign talent, together with a failure to cultivate an adequate domestic science and engineering workforce, threatens a decline in American health, prosperity, and national security. (p. 10)

> *Conclusion: The solar and space physics workforce includes a significant number of researchers educated or trained abroad, and the workforce can be expected to evolve with global political and societal changes. The reliance of the U.S. solar and space physics research on foreign-born and -educated talent needs to be recognized.*

4.2.3 Workforce Needs of the Future

The workforce is changing and will continue to change in the coming years. At the same time, the needs of the field are evolving. Intrinsic to the science themes from Chapters 2 and 3 is the need for expertise in various areas, including but not limited to computer and data science, artificial intelligence, machine learning, big data, software development, industry-specific engineering. Techniques and advancements made in the finance and technology sectors can also be highly relevant. This broadening of knowledge areas that can contribute to the field, along with academically engaging projects, might attract individuals with those skill sets, benefitting the field with their expertise.

Solar and space physics has traditionally been siloed into several subareas, with little overlap or blending areas across them. Moreover, there has been no efficient outreach to other fields that are connected either through research topics or methodologies. The committee's vision for the future of the field changes that perspective to one that is outward facing and promotes collaborating across disciplines. Figure 4-10 shows the myriad disciplines that meet and overlap to define the expanding concept of solar and space physics.

> *Conclusion: Solar and space physics research benefits from an emphasis on interdisciplinary teams with overlapping expertise. Such teams can involve experts in applied math, space weather prediction, machine learning, data management, and computational applications, among others, working with solar and space physics scientists to achieve the research goals.*

Physics degrees represent a pathway that can lead to a variety of high-tech careers other than physics research. The finance, technology, and the energy sectors in particular, and other industries and government entities in general, highly value the skills that are developed through a standard physics education. The growth of the space industry and space weather applications industry has created a new job market for solar and space physics experts at various levels. Conversely, solar and space physics research teams increasingly include experts from other

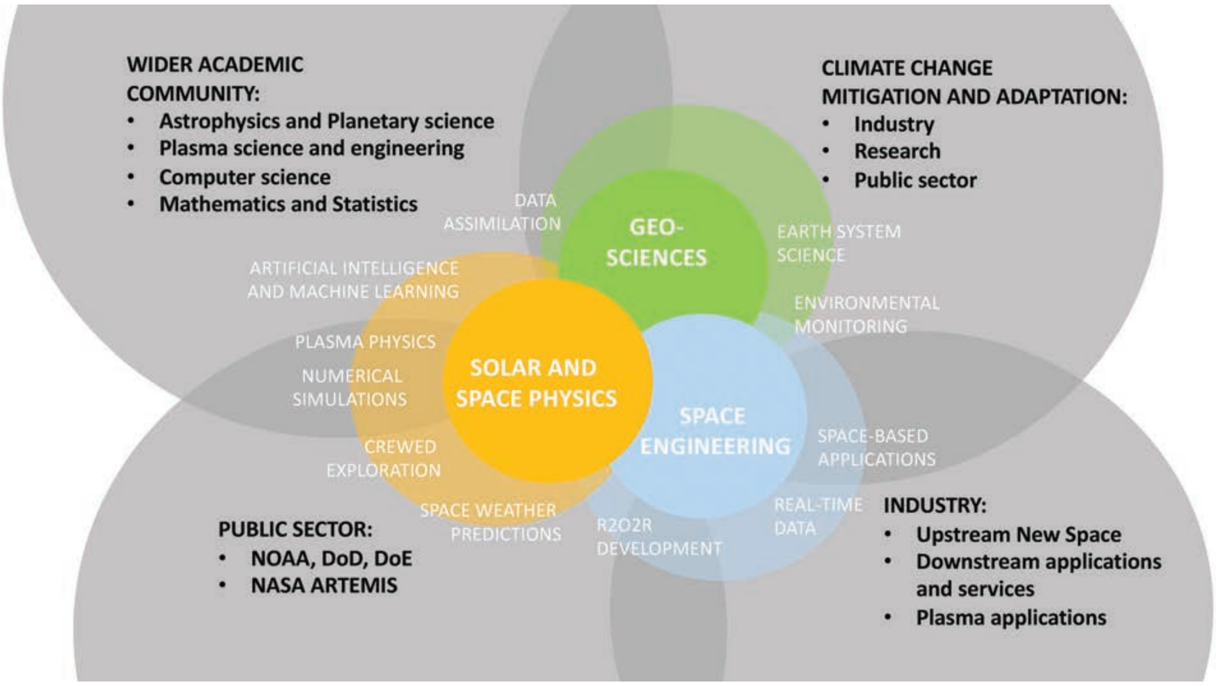

FIGURE 4-10 The evolving subject matter, workforce, and customers of solar and space physics.
NOTE: DoD, Department of Defense; DoE, Department of Energy; NASA, National Aeronautics and Space Administration; NOAA, National Oceanic and Atmospheric Administration; R2O2R, research-to-operations-to-research.

high-tech careers. To attract top talent to the myriad fields that involve solar and space physics, students need to be exposed to the science and the career opportunities associated with it as early as possible and at the very latest in general undergraduate courses. Data scientists, computer scientists, and others with those skill sets will be more attracted to job opportunities in solar and space physics research fields if they have previously been introduced to and engaged in those fields.

Conclusion: Solar and space physics needs to engage with professionals in engineering, computer science, and management, to encourage pathways into projects in the solar and space physics fields. A solar and space physics consortium could coordinate these efforts.

Related to this new, expansive definition of the field and the workforce that underlies it, there are needs that require attention in moving forward into the next decade. The rest of this chapter details how to best support this expanding and evolving workforce and how to cultivate that workforce to attract those most enthusiastic about discovery in solar and space physics.

4.3 THEME 2—SOLAR AND SPACE PHYSICS EDUCATION

4.3.1 Incorporating Solar and Space Physics in K–12 and College Education

To raise public awareness of solar and space physics and to broaden the career options in the field, the subject needs to be introduced in K–12 education and incorporated into classes from undergraduate to MS to PhD curriculums. This broader education is also necessary in areas other than physics, including astronomy; applied sciences, such as aerospace and electrical engineering; and environmental science programs. College education is the backbone of recruitment into the field, as well as the best mechanism for raising public awareness about the importance of solar and space physics research. K–12 education ensures that college programs attract the best students from diverse backgrounds.

To illustrate the depth of the issue, examples of several prominent undergraduate introductory astrophysics and general education astronomy textbooks that are nearly devoid of solar and space physics topics include: *The Cosmic Perspective: The Solar System* (Bennett 2019), *An Introduction to Modern Astrophysics* (Carroll and Ostlie 2017), and *Astronomy* (Fraknoi et al. 2016). Also often missing from the content are the foundational drivers of space weather—the magnetic fields and plasmas emerging from the solar surface, filling interplanetary space with the solar wind, and interacting with the geomagnetic field. Rather, the focus is only on interior processes of the Sun and geomagnetism as it relates to Earth's geology, with the space science component omitted entirely. Fraknoi et al. (2016) is the only text to mention the consequences of space weather, but it does so without explaining the role of magnetic fields or plasma.

Many students who are not majoring in STEM studies take general astronomy courses to fulfill a natural science requirement with a topic in which they are interested (Impey and Buxner 2020). For a vast majority of these students, the astronomy course will be their last exposure to formal science education. Some progress has been made to include solar and space physics material into undergraduate education by either incorporating material into undergraduate courses or by teaching a class on space weather or space science. These are individual solutions that are undertaken by only a few professors at a handful of universities across the country. In other cases, undergraduate material about space weather is often discussed in terms of hazards. This approach is in contrast to the way in which hurricanes or volcanoes are discussed in the context of a desire to understand the natural world, in addition to teaching about their effects. An incredible opportunity exists to build topics in solar and space physics into full courses or to integrate them with astronomy to create student and public consciousness about the field. This opportunity is not currently being leveraged to its full potential.

At the K–12 level, the implementation of discipline-specific subject matter is more complex since schools are often teaching to well-defined curricula with very narrow learning objectives. However, many educators are free to enhance the standard material with extra topics that catch the students' interest, especially if that material contains concepts related to the primary curriculum. Several examples include an app-based textbook developed by Big Kid Science, *Totality*, which focuses on solar eclipses but also has much of the science background included in an accessible way. Other examples are a general solar and space science textbook aimed at middle and high school levels, *Solar Science* (Schatz and Fraknoi 2016) and a PDF textbook available from NOAA's Space Weather Prediction Center aimed at junior high and high school students, *Solar Physics and Terrestrial Effects* (Briggs and Carlisle 2016). Finally, there are multiple examples of curriculum-enhancing resources that have been produced through one-off grant opportunities, such as Space Weather UnderGround, started at the University of New Hampshire[2] and being expanded to the University of Alaska Fairbanks.[3]

There have been several concerted efforts to present space physics to students at the undergraduate level, starting with *Introduction to Space Physics* by Kivelson and Russell (first edition, 1995). *Understanding Space Weather and the Physics Behind It* by Knipp (2011), and *An Introduction to Space Weather* by Moldwin (2008)—both focusing on space weather—attempt to appeal to a general science audience. However, to effectively reach a broader audience, modest sections on space sciences are needed in the standard textbooks, including those in Earth sciences, atmospheric sciences, and environmental sciences, as well as the full range of physics and aerospace texts from introductory undergraduate to graduate levels. Furthermore, imaginative, colorful graphics could make the Sun and magnetosphere as familiar to middle school and high school students as the globe of Earth and help with retention of information on solar and space physics (Bobek and Tversky 2016). Relatable, real-life examples would extend the reach of the material, and interactive activities would engage students on a deeper level (Goldberg et al. 2010). All these resources require significant input from the current space physics

[2] University of New Hampshire Institute for the Study of Earth, Oceans, and Space, "Space Weather Underground," https://eos.unh.edu/space-science-center/outreach/space-weather-underground, accessed May 21, 2024.

[3] University of Alaska Fairbanks Space Weather Underground, "Space Weather Underground Project," https://sites.google.com/alaska.edu/swug/home, accessed May 21, 2024.

community; they could be produced through add-on, supplemental funding to research and analysis projects, as well as missions.

Conclusion: Solar and space physics science has not been fully incorporated into U.S. education at either the K–12 or undergraduate level in the same way that astronomy and astrophysics, Earth sciences, and planetary science have been. Consequently, the recruitment of students and professionals into solar and space physics is less than it could be.

Conclusion: The absence of exposure to solar and space physics in K–12 or early college courses means many students are unaware of the field. To meet future workforce needs and attract talented STEM students from a broad range of backgrounds, solar and space physics needs to be promoted through early educational experiences, in which a solar and space physics consortium could play a significant role.

Recommendation 4-2: Funding agencies should expand the reach of solar and space sciences in education by expanding the definition of the National Science Foundation's "broader impacts/societal impacts" and the National Aeronautics and Space Administration's "broadening impacts" to specifically include developing solar and space science educational materials aimed at K–12 and college students.

4.3.2 Implementing Education and Student Recruitment

Increasing the Number of Faculty in Solar and Space Physics

One major factor limiting the exposure of students to solar and space physics is the lack of scientists in this field on the faculty at universities. As noted above, creating the foundations of a strong workforce requires cultivation of significant interest in solar and space physics early on in college as students start to assess options for future career pathways. Education is key to this mission.

University professors often teach large "service" courses that expose a variety of students from majors other than physics or astronomy. There is an enormous untapped opportunity to reach that same number of students with topics centered around solar and space physics and discuss their relevance to society. In addition, university faculty and researchers often employ students as research assistants, including those with backgrounds in physics and astronomy, engineering, mathematics, and even chemistry or biology. This is yet another way to expose students to research at a crucial point in their decision-making process related to future career goals. Finally, university faculty often engage in large-scale public outreach, including K–12 students. Activities can include public demonstration events; public night-sky observing nights; classroom visits; summer internship and research experience activities; event-specific outreach, such as events revolving around solar eclipses; and discipline-specific organizational events, such as the Conference for Undergraduate Women in Physics, the American Physical Society student conferences, and the physics congresses organized by the Society of Physics Students (PhysCon). These activities can serve to initiate the first sparks of interest that may attract students to the field. Additionally, minority-serving institutions represent an important untapped resource for recruiting students into the field (NASEM 2019).

University faculty and researchers represent the fulcrum of this interaction, serving as a bridge between public and professional, education and expertise. Furthermore, university faculty are the ones providing the intensive student training, through grants and awards, necessary to grow the future workforce in solar and space physics. Currently, there is additional pressure to this already strained system in the form of shuttering departments, colleges, and entire institutions as the college-bound population shrinks.

Conclusion: University PIs and faculty who teach courses and have major research support are well positioned to broaden the reach of solar and space physics education, as well as provide focused training to students already engaged in those sciences.

The Faculty Development in geoSpace Science (FDSS) opportunity created by the NSF Division of Atmospheric and Geospace Sciences (AGS)[4] created a significant increase in the number of solar and space physics faculty at national educational institutions. This competitive program funds the creation of new tenure-track faculty positions at U.S. universities and colleges by offering 5 years of salary funding and start-up resources to an institution as a means of encouraging hiring in the specific area of solar and space physics in science, engineering, or related departments. This incentive can be highly attractive to an institution and thus represents an opportunity for a department to hire in this area and gain a coveted faculty position for solar and space physics.

Since the first cohort of FDSS faculty members was hired in 2004, NSF has increased the cadence of FDSS opportunities, which has been beneficial to solar and space physics. Seventeen faculty members have been hired through the FDSS program: eight in 2004, two in 2014, and seven in 2019; only two have left the institution for which they were hired in an FDSS position. All but one faculty member hired prior to the 2019 competition have been tenured. The one exception became a director for a renowned university-based space physics laboratory. Thus, the FDSS program has been highly successful at promoting early career researchers into positions through which they can contribute to the field in a significant way, including in educational and mentorship roles.

While it can be beneficial to establish new solar and space physics group, faculty members are often more successful in organizations where there are multiple researchers and professors working on similar topics in one location, a "critical mass." A faculty cohort can share resources, host seminar speakers, recruit students and postdocs, and achieve adequate class enrollments. However, institutions that have previously received an FDSS award are ineligible to submit additional proposals (NSF 2023), which may leave new FDSS faculty members without a meaningful support network and mentoring. Allowing a previous FDSS institution to propose again is one way to alleviate that possibility and achieve critical mass. Another way to achieve critical mass is through cluster hiring, hiring more than one emerging researcher at the same time to form a cohort. In some cases, cluster hires have been extremely productive, leading to research and mentoring success as well as a higher satisfaction with the positions. Cluster hiring could deepen the value of the FDSS program and improve the likelihood of maintaining a strong solar and space physics program at a particular university (see NASEM 2022a).

NSF has already started implementing targeted FDSS opportunities to minority-serving institutions and emerging research institutions, which is a potentially transformative change. However, the FDSS program does not target teaching-oriented (non–research 1 [R1]) institutions. The potential of these institutions for strengthening and diversifying the STEM workforce has been previously identified (NASEM 2019); faculty development in solar and space physics at these institutions could help to leverage this underused resource. Mentor–mentee partnerships between teaching-oriented and R1 institutions are supported in other disciplines by NSF and the Department of Defense and could be an additional model to consider. In all cases, ensuring that new faculty have adequate support and mentoring is critical for their success.

Conclusion: The FDSS program has been successful in expanding solar and space physics to more and different types of universities. Expanding the program by allowing cluster hiring applications from existing strongholds of solar and space physics and continuing targeted calls for minority-serving institutions could be beneficial for the success and longevity of solar and space physics faculty at FDSS institutions.

Recommendation 4-3: The National Science Foundation (NSF) should continue and expand support for the Faculty Development in geoSpace Sciences (FDSS) program in solar and space physics at universities. Specifically, the cadence of opportunities should be increased and occur on a regular schedule, and the number of hires for each new opportunity should be approximately the same.

[4] "The Geospace Section of the NSF Division of Atmospheric and Geospace Sciences (AGS) offers funding for the creation of new tenure-track faculty positions within the disciplines that comprise the AGS Geospace programs to ensure their vitality at U.S. universities and colleges. The aim of the Faculty Development in geoSpace Science (FDSS) is to integrate topics in geospace science including solar and space physics and space weather research into natural sciences or engineering or related departments at U.S. institutions of higher education (IHE)." U.S. National Science Foundation. April 6, 2023. "Faculty Development in geospacer Science (FDSS)." See https://new.nsf.gov/funding/opportunities/faculty-development-geospace-science-fdss.

NSF should consider allowing proposals for cluster hires and allowing previous FDSS institutions to propose again.

Expanding Opportunities for Student Research

Solar and space physics would benefit from efforts to expand the reach of research opportunities in solar and space physics. Such an expansion would aid in recruitment efforts, and top talent would be more easily attracted to the field after having exposure to research. As discussed above, many university faculty lead these kinds of research opportunities at educational institutions, but there are also examples of summer internships, schools, and other training activities hosted by national and government labs, as well as university-affiliated research centers: see Figure 4-11.

The *Advancing Diversity* report (NASEM 2022a) found that, "Decades of educational research suggest that early and ongoing experiences with authentic research—experiences that engage students not only in learning about but actually doing research—is key to retaining students generally and URM [underrepresented minority] students specifically" (p. 76).

Long-standing hallmark programs include NSF REUs, NASA's Heliophysics Summer School, and NSF's Space Weather Summer School, as well as such funding opportunities as Future Investigators in NASA Earth and Space Science and Technology (FINESST) fellowships (previously the Graduate Student Researchers Program), the NSF Graduate Research Fellowships Program, the NSF Integrative Graduate Education and Research Traineeship Program, and the NASA National Space Grant College and Fellowship Project opportunities offered through state universities. In addition to these relatively centralized programs, summer schools, internships, research appointments, and student workshops have been supported by individual PIs and faculty members or teams of researchers. These programs are hosted by a variety of institutions, from university campuses to government laboratories, such as the Los Alamos National Laboratory and the year-long National Astronomy Consortium program at the National Radio Astronomy Observatory.

Every research opportunity plays a unique role in an ecosystem of experiences available to students. This ecosystem needs to be fostered and encouraged to grow, in various directions, to provide opportunities for all interested students. These opportunities can be facilitated in many ways (e.g., through expansion of REU programs), and by increasingly allowing researchers to request funding supplements to support new or expanded research opportunities, especially ones that use novel methods of connecting with students. Support for a variety of research opportunities can help bring in more students by providing options other than the full summer research experiences that require relocation. Shorter, immersive undergraduate experiences that last for 1–2 weeks can be attractive to a different subset of the student population than the traditional 8- to 12-week REU experience, particularly students who need full-time jobs in the summer months or have personal or family commitments (Jaynes and Meerdink 2022). To this point, such research experiences need to be funded adequately such that students are paid a living wage to attend, and travel and housing costs are deferred. Participation options can be expanded as well, by offering hybrid attendance options or virtual connectivity at staggered times for small cohorts of students in different time zones.

As these experiences form a critical part of training for both undergraduate and graduate students, agencies could encourage hosts to include skill-building activities in their research experience programs. These activities could focus not only on exposure to science training and research skills, but also on collaboration and career building. Examples could be seminars and meant to improve collaborative working skills and enhance positive team dynamics in a group, as well as such interpersonal skill-building activities as mini-workshops on bystander intervention and microaggressions. A solar and space physics consortium could be helpful to pool resources for these experiences, share best practices, and assist in advertising to undergraduate and graduate institutions.

Recommendation 4-4: Funding agencies should expand the reach of solar and space physics by increasing funding opportunities for researchers to lead summer schools, workshops, and other skill-building activities for undergraduate and graduate students. Funding these activities should include time for the researchers who lead them as well as resources, such as paid stipends to address equity, for the students. Such research supplements should require gathering and reporting data on participants, activities, and their impact.

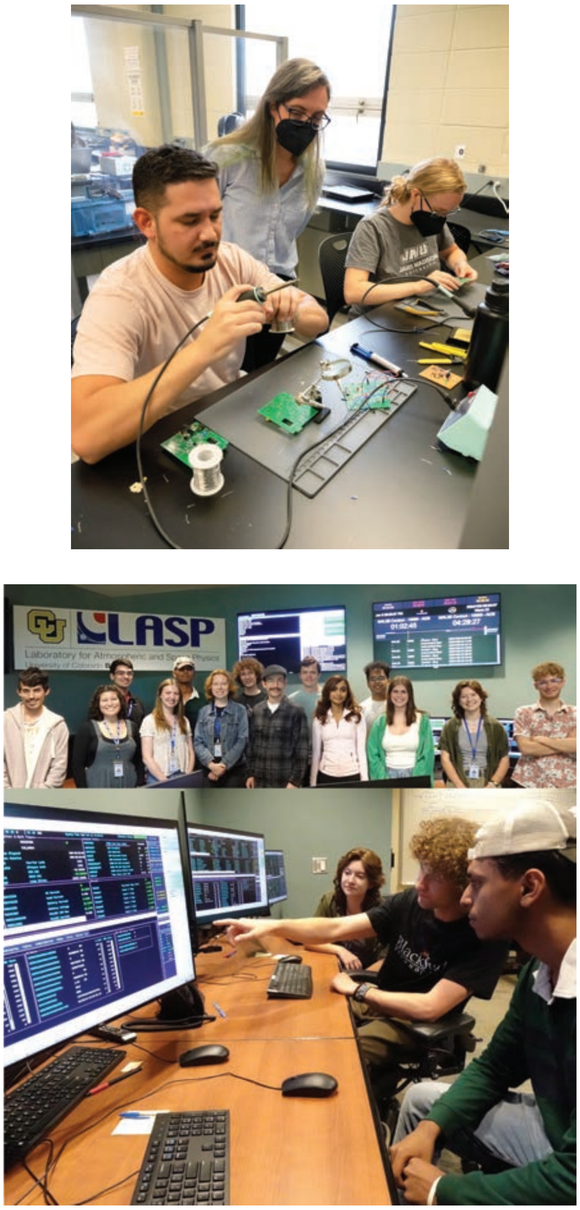

FIGURE 4-11 Student engagement with missions: the top figure shows a professor and students at the Edge of Space Academy in 2022 soldering boards for instruments to be flown on drones and high-altitude balloons; the middle and bottom figures show University of Colorado undergraduate students being trained as operators for Science Operation Centers at the Laboratory for Atmospheric and Space Physics.
SOURCE: (*Top*) Courtesy of Allison Jaynes, University of Iowa; (*Middle and Bottom*) Courtesy of Fran Bagenal, University of Colorado Boulder.

4.4 THEME 3—DEIA+

4.4.1 Building Awareness

The report of the Panel on the State of the Profession (Appendix F) suggests creating or continuing committees that focus on DEIA+ initiatives (Suggestion 4) and considering current best practices, such as acknowledging and adjusting for the common incorrect beliefs that continue to be perpetuated. There are many challenges: Change-resisting gatekeepers make institutional change difficult, and universities in some states have lost their DEIA+ organizations and others are adapting to the recent Supreme Court decision (*Students for Fair Admissions, Inc. v. President and Fellows of Harvard College* 2023). Making changes throughout the institution is challenging as often it is the same people, time after time, who attend DEIA+ awareness training and outreach sessions. Unconscious bias is pervasive and affects the review of proposals, interactions among colleagues, and the actions of program officers and supervisors at all levels. Changing the still-existing cultures that protect harassment and exclusion requires creative and progressive methods to dismantle them by the agencies, and by extension the community. Furthermore, university DEIA+ programs can have a role in improving the culture of academia, particularly at the early stages of student careers. Organizations such as the American Physical Society offer to set up a visiting committee to carry out climate studies at academic departments and institutes (APS 2024). These committees can identify and suggest steps to mitigate adverse conditions in the workplace

Various reports have distilled best practices that can be followed for advancing DEIA+ in the solar and space physics communities, including *Advancing DEIA in the Leadership of Competed Space Missions* (NASEM 2022a); *Foundations of a Healthy and Vital Research Community for NASA Science* (NASEM 2022b); and in the sciences in general, such as *Unequal Treatment Revisited* (NASEM 2024) *and Minority Serving Institutions* (NASEM 2019). The question then needs to be asked: Why has such little progress been made in this area?

The recent Heliophysics Division Inclusion, Diversity, Equity, and Accessibility working group, which is the Heliophysics arm of the NASA Equity Action Plan (NASA 2023a), is a positive step in the direction of strategic DEIA+ advances. The group has been charged with several tasks, including recommending action and policy changes that align with the DEIA mission of the Heliophysics Division. Building on successful implementation is key, such as NASA's Bridge Program, which aims to develop partnerships with historically under-resourced institutions while engaging in NASA science. It is too early yet to assess the overall success of these newer programs. The NSF Significant Opportunities in Atmospheric Research and Science (SOARS) program, managed by the University Corporation for Atmospheric Research, is an example of the highly successful implementation of a bridge-style program. SOARS mentors students who identify as historically marginalized in science in the undergraduate-to-graduate school transition phase and provide research experience opportunities. Their long-term trends are impressive: over 90 percent of SOARS program participants continue to graduate school (UCAR 2024).

Conclusion: The solar and space physics community and funding agencies need to identify and be aware of barriers for people from historically marginalized groups in STEM who work in the field and jointly address the need to be more inclusive.

The report of the Panel on the State of the Profession, as well as the reports cited above include a wealth of knowledge and suggestions that could be considered by relevant invested parties as they work to craft meaningful actions. Here is another avenue in which a solar and space physics consortium could be immensely beneficial, by aggregating resources and coordinating dissemination to researchers, as well as compiling assessments of ongoing programs.

4.4.2 Enhancing DEIA+ in Research

DEIA+ represents a wide range of topics, encompassing diversity, equity, inclusion, accessibility, anti-racism, accountability, and more. The report of the Panel on the State of the Profession (in Appendix F) includes an extensive discussion on the definition of this all-encompassing term and the implications it has for how research is conducted in collaboration with others. Effort and attention going toward DEIA+ actions repay the work several times over by building a community of supportive, enthusiastic researchers who are excited to collaborate, eager to help each other, and feel safe and respected in their working environments. While this report focuses on specific activities that are within the scope of research grants and contracts and can thus be implemented in the near future, there are many additional suggestions in the panel report that are worth careful consideration by the relevant agencies. In particular, one aspect directly within agencies' purviews, related to proposal DEIA+ plans, can be addressed at this time, as discussed below.

According to *Science 2020–2024: A Vision for Scientific Excellence*, one of NASA's strategies is to "increase the diversity of thought and backgrounds represented across the entire SMD portfolio through a more inclusive environment" (NASA, 2020 [updated 2023], p. 23). In 2021, NASA began piloting requiring inclusion plans as part of research proposals. The ways in which an inclusion plan can meet these needs are varied, and SMD provides a short list of references about inclusion plan pilot programs and barriers to inclusivity in STEM overall.[5] Several of the relatively large programs in Heliophysics already require diversity and inclusion plans, including the Explorers program,[6] DRIVE Centers, and Space Weather Centers of Excellence. Currently, there is a pilot program to extend the requirement to other program elements in the Research Opportunities in Space and Earth Sciences (ROSES) framework. ROSES 2024 states that inclusion plan evaluations currently "will not contribute to adjectival ratings or selection recommendations" for proposals (NASA 2024c, p. 8).

DEIA+ plans developed as part of research proposals encourage the project team to consider and discuss all the issues encompassed by the term. Teams reflect on ways they are best positioned to contribute to positive changes within the DEIA+ space. Explicit inclusion of such plans also ensures that sufficient resources are dedicated by the project to the promotion of DEIA+ ideas. While successful DEIA+ plans need to have built-in evaluation metrics and techniques for periodic assessment, metrics are not required in the current DEIA+ system. A subpanel of DEIA+ experts on all the panels that assess large missions or research proposals would be able to provide guidance and feedback on the DEIA+ plans of the proposing teams.

Additionally, when possible, supplemental funding channels could be made available to groups that wish to go above and beyond with DEIA+ initiatives that may require the involvement of professional organizations or individuals or otherwise require more resources than are generally accounted for in the course of a standard DEIA+ portion of a large proposal. Furthermore, those researchers submitting smaller proposals that do not require DEIA+ plans need to be able to access supplemental funding if they wish to include a DEIA+ component that requires additional resources. Such new funding channels would work best if they are transparent and clearly communicated to the community (because not everyone is familiar with what comprises a DEIA+ activity). An analogous example of supplemental funding for a separate purpose is the NASA Supplements for Open-Source Science which supports the addition of an open science component to an existing award. A similar model could be used to support DEIA+ activities. Supplemental funding opportunities would support those who wish to participate in advancing DEIA+ goals without overburdening smaller projects with additional requirements.

Time and effort dedicated to DEIA+ activities in the current environment are slowed down by the lack of understanding of the types of activities that fall under this category and by the lack of visibility, merit, and explicit recognition of those activities. It would be beneficial for agencies to disseminate examples of successful DEIA+ initiatives (with involvement by the PIs) to the community. These would provide a template for successful future DEIA+ plans and would recognize the PI and the team for an aspect of their work that is often not rewarded. Sharing of successful strategies (and ones that did not work) needs to become more commonplace and could be better facilitated by the agencies. Simple actions—such as wide social media engagement with positive DEIA+ messaging, mentorship networks and training, awareness seminars about various topics, and broad recognition of colleagues and contributors—are all robust examples of DEIA+ initiatives that can be part of a larger plan: see Figure 4-12. Agencies can collate and summarize these actions as part of materials that are developed to guide PIs when they are producing their custom DEIA+ plans as part of their preproposal activities.

A further challenge in implementing DEIA+ plans is that they are often poorly tied to broader efforts that are already under way. Almost all universities and research institutions have their own DEI plans and actions, but the proposed activities seldom directly draw from these resources. Similarly, agencywide efforts in DEIA+ are almost never available to proposers, leaving them to design plans of their own, which may be less effective than plugging into existing networks and frameworks. More attention needs to be placed on promoting and inviting researchers to partner with agencies to take advantage of ongoing activities. The frustration that many researchers feel when

[5] NASA, "Inclusion Plan Resources," updated May 2024, https://science.nasa.gov/researchers/inclusion.

[6] The 2022 Small Explorers call for proposals required a two-page diversity and inclusion plan. One of the evaluation factors for the proposal is the probability of science team success, including the diversity and inclusion plan (NASA 2022).

FIGURE 4-12 SHIELD Drive Science Center webinar on the experience of queer scientists, showing an example of a DEIA+ initiative as part of a large NASA proposal activity.
SOURCE: Image courtesy of the SHIELD DRIVE Science Center, https://shielddrivecenter.com. Image credit: Victoria Pereira.

having to develop their own DEIA+ plans can be avoided by publicizing and encouraging these partnership opportunities. Lastly, education and public outreach initiatives often overlap directly with the goals of DEIA+ activities and can therefore be leveraged to make science more accessible in a variety of ways.

Recommendation 4-5: To be proactive about enhancing DEIA+ (diversity, equity, inclusion, and accessibility, as well as anti-racism, accountability, and justice) across the solar and space physics workforce including recruitment, working environments, and retention for all research and mission teams, all the relevant agencies, including the National Aeronautics and Space Administration and the National Science Foundation, should, when possible:

- **Continue and enhance funding of DEIA+ activities by (1) requiring DEIA+ plans for large proposals (more than $1 million) and (2) making supplemental funding available for optional DEIA+ activities as part of proposals;**
- **Enhance the opportunities for the science community to participate in existing host organization–based or agencywide DEIA+ efforts; and**
- **Improve the quality and review process of proposed DEIA+ plans by (1) providing sample activities or successful examples of DEIA+ plans to the community; and (2) reviewing DEIA+ plans associated with large proposals in panels whose members have the appropriate expertise to provide concrete and constructive feedback for improvement.**

Many of the topics addressed within this theme and recommendations to promote change have been described at length in prior reports, including NASEM (2022a,b). These prior discussions contain valuable information not repeated here, including the use of dual-anonymous proposal review processes and active education about the unintentional biases that inform decision-making and how to combat those instincts.

4.5 THEME 4—EXPANDING PUBLIC OUTREACH AND PARTICIPATION

4.5.1 Public Communication and Materials

Public outreach has far-reaching effects on education, policy, legislation, and public opinion. Public engagement can be achieved in myriad ways: encouraging citizen science participation, science communication pathways, and tie-ins to art and literature, and leveraging of popular culture, social media, and more. Popularizing the science of solar and space physics increases attention and supports the field to embark on ambitious discoveries. The excitement that is generated by rallying around large discoveries (e.g., the Apollo and Voyager programs) is invaluable for public outreach and ripples outward for decades. Notable recent efforts include the Heliophysics Big Year (NASA n.d.) and The Sun, Moon, and You (NOAA) efforts that encourage individuals to celebrate the Sun and its influence on Earth and the solar system. These efforts capitalized on the 2023 and 2024 annular and total solar eclipses and the Parker Solar Probe mission's closest approach to the Sun: see Figure 4-13. However, outreach efforts need to be sustained and expanded to have a significant influence on the public.

FIGURE 4-13 The Great American Eclipse, on April 8, 2024, was observed by millions of people, and provided a unique opportunity to engage with the public and citizen scientists around the country. (*Top*) Composite image of the eclipse progress over the Washington Monument. (*Bottom*) graphic from NASA's promotional material for eclipse events.
SOURCE: (*Top*) NASA/Bill Ingalls; (*Bottom*) NASA/Kristen Perrin.

One way to increase visibility is through so-called STEAM initiatives, or STEM plus art, by fostering art exhibits, printed materials in collaboration with artists and writers, and visual art projects. Agencies can promote these activities by leveraging STEAM partnerships and collecting current best practices in engaging the public through outreach to communities and education centers. Previous successful outreach campaigns can be assessed, evaluated, and used as models for future efforts, using resources from the agencies earmarked for this purpose. A solar and space physics consortium could aid with this task.

Conclusion: The space science community needs to have a data bank of resources and materials to draw from that communicate to the public what solar and space physics is and how it affects society. Such a data bank would include enticing, impactful, and regularly updated material accessible on the websites of all relevant agencies, including NASA, NSF, and NOAA.

Various opportunities for connecting with the public are not being well leveraged. For example, the National Air and Space Museum in Washington, DC, contains only a small space weather display, without offering the context of the solar system surrounding Earth or the many ways the Sun influences it. Additionally, very few examples related to solar and space physics are currently available on the NASA+ website (NASA 2024b). Some of these deficiencies may be addressed by better organization of strategic communications and outreach offices within the agencies. Agencies can focus on efforts to make the science of solar and space physics more accessible, including overhauling the public-facing websites serving the discipline.

4.5.2 Citizen Science

"Citizen science," sometimes called participatory science, refers to collaborative work between teams of scientists and nonscientists. Typically, citizen scientists engage in identification or classification of phenomena by combing through previously collected data, or they collect data themselves through the use of photography, audio recording, and other collection methods available to them. One of the biggest success stories of citizen science in the solar and space physics domain came from the discovery of STEVE, an upper atmosphere strong thermal emission velocity enhancement (MacDonald et al. 2018). This work is continued by a public–private collaboration between aurora-watchers, the University of Calgary, and Aurorasaurus, a citizen science site where one can report sightings of the aurora around the world (see Figure 4-14).

Another recent and engaging citizen science project is the NASA-funded HARP: Heliophysics Audified: Resonances in Plasma. HARP offers a graphical interface online (Figure 4-15) where participants can listen to plasma wave observations from spacecraft that have been translated to audio frequencies. Participants identify patterns in the audio to help researchers pick out specific events within a vast data set.

Professional societies, together with nonprofit STEM partners, can help connect and engage those interested in and involved with citizen science to add pathways into the solar and space physics braided stream and enable science literacy, science communication, and public engagement (see Figure 4-7, above).

Recommendation 4-6: Funding agencies should increase the volume and dissemination of materials that communicate solar and space physics research results and their societal impacts to the general public. The National Science Foundation and the National Aeronautics and Space Administration should increase outreach programs related to active missions, ground-based facilities, and research and expand support of citizen science and participatory science.

The community is enthusiastic about participating in outreach activities but adequate funding mechanisms either do not exist or are not obvious. The current NASA SMD Science Activation program is a good example of a starting point for these kinds of initiatives.[7] More efforts in these areas are needed to bolster public support of the science of solar and space physics.

[7] For more information, see the NASA SciAct program and the 2020 NASEM report *NASA's Science Activation Program: Achievements and Opportunities*.

FIGURE 4-14 Aurora Chasers card game as public outreach from Aurorasaurus: an example of citizen science coupled together with STEAM activities to serve as outreach.
NOTE: STEAM, science, technology, engineering, art, and mathematics.
SOURCES: (*Top row*) Aurora Chasers is an educational card game created by Aurorasaurus, a participatory science project supported by NSF and NASA. The game is openly licensed under CC BY-NC-SA; (*Bottom row*) Aurora Chasers is an educational card game created by Aurorasaurus, a participatory science project supported by NSF and NASA. The game is openly licensed under CC BY-NC-SA. Card photos shown are generously provided by Aurorasaurus Ambassadors Vincent Ledvina, Rocky Raybell, and Chandresh "CK" Kedhambadi, and are reproduced with permission.

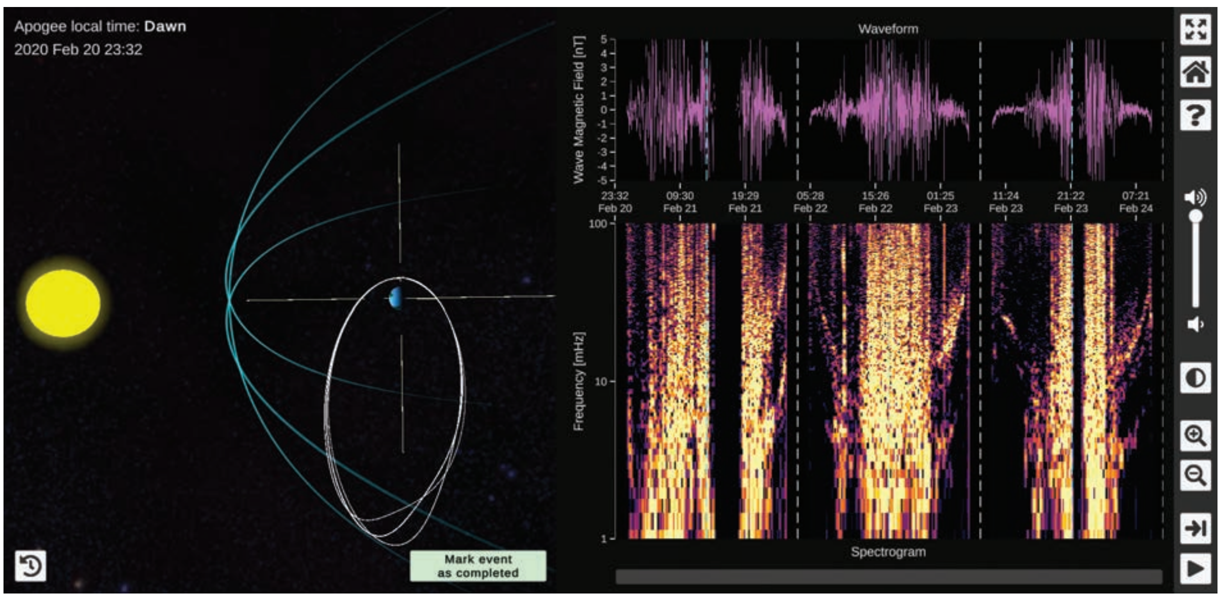

FIGURE 4-15 Heliophysics Audified: Resonances in Plasma is a tool for citizen scientists to mark plasma wave events as identified by listening to those waves translated into audible frequencies.
SOURCE: Heliophysics Audified: Resonances in Plasmas Team (Space Science Institute, UCLA, Virginia Tech, Auralab Technologies Inc., Imperial College, NASA GSFC, NOAA/NCEI)/Space Science Institute.

One method is for agencies to enhance funding for the "broader impacts" components of proposals (including those for NASA grants and missions). The inclusion of material related to public outreach in those sections of proposals could be encouraged as one means of fulfilling the broadening impacts requirements, depending, of course, on the interest level of the proposers. Pending additional funding, supplements to awards could be offered to proposers who wish to embark on larger outreach and education projects. More work can be done to facilitate outreach and broader impacts as part of mission projects in the framework of the agencies' own efforts.

4.6 SYNOPSIS

This chapter emphasizes two key points: that the research profession of solar and space physics needs the necessary workforce to address the science goals and that the necessary healthy, vibrant, diverse workforce will not be appropriately educated and trained unless funding increases. As the field develops—including into applied areas, such as space weather and across interdisciplinary boundaries—education and training need to broaden into different fields. To keep track of the evolving workforce, demographic data need to be regularly gathered across the whole field.

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SOURCES FOR IMAGES IN FIGURE 4-1

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5

Comprehensive Research Strategy: A HelioSystems Laboratory and Supporting Research and Technology

5.1 INTRODUCTION

The comprehensive and balanced research strategy presented in this chapter builds on the solar and space physics mission statement with its two interlinked themes (Figure 5-1).

As requested by the sponsors through the statement of task, the research strategy to advance solar and space physics science and space weather research is ambitious, but also realistically achievable. This research strategy was developed to enable significant progress on the focus areas identified and motivated in Chapters 2, 3, and 4. This section presents a high-level summary of the strategy. Details and specific recommendations are presented in Sections 5.2–5.4.

The scientific research discussed in Chapter 2 focuses on three themes: studying Sun–Earth–Space as an interconnected system, understanding the underlying physical processes that are the basic building blocks of this system, and exploring our cosmic neighborhood and beyond. Under the three scientific research themes (see Figure 2-1) are guiding questions, three for each scientific research theme, and under these guiding questions are focus areas. It is through these science focus areas that progress is made on answering the guiding questions.

The space weather research discussed in Chapter 3 also focuses on three themes: systems of systems drivers, responses of the physical system, and impacts on infrastructure and human health. Notably, the three space weather research themes are interlaced with the science themes. Different from the science themes, space weather research is driven largely by the needs of space weather users. Therefore, the three space weather themes (see Figure 3-2) have focus areas that lead to specific operational outcomes for space weather.

Further unifying basic scientific research and space weather application is the realization that advancement of both requires a vibrant and engaged solar and space physics community. The four themes that develop and transform the community, described in Chapter 4, are the following: demographics, space science education, DEIA+,[1] and expanding public outreach. For the enrichment of the community over the next decade, these four themes (see Figure 4-1) lead to five recommendations.

The comprehensive research strategy, which that grew out of the science, space weather, and state of the profession themes discussed in the previous three chapters, is both ambitious and realistic. *Ambitious* to mirror

[1] DEIA stands for diversity, equity, inclusion, and accessibility, a phrase used to define policies, behaviors, and beliefs that support the opportunity for all to participate and develop within a community. The "+" includes anti-racism, accountability, and justice.

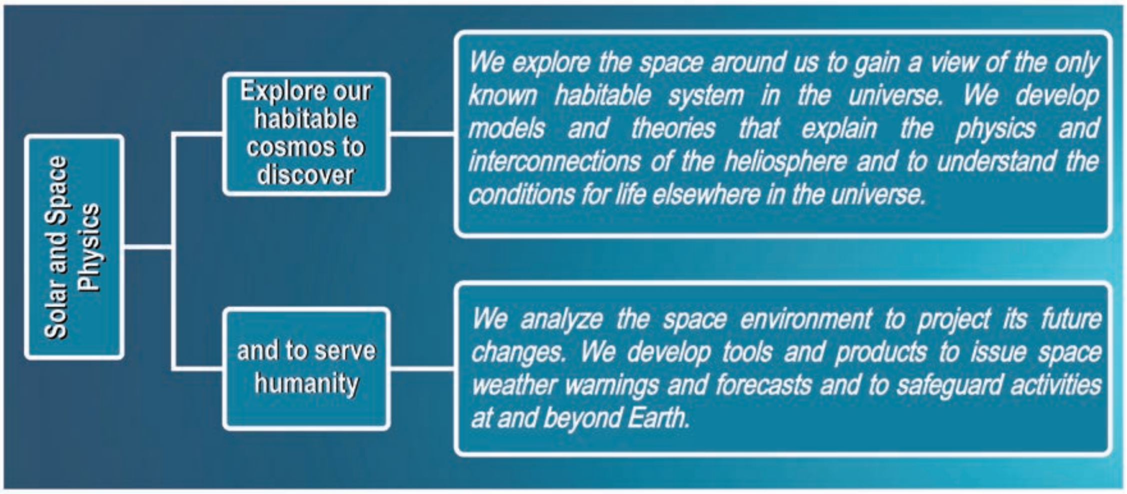

FIGURE 5-1 Mission statement for solar and space physics. The research strategy presented in this chapter builds on this two-pronged mission statement.
SOURCE: Created by AJ Galaviz III, Southwest Research Institute.

the ambitious science and space weather guiding questions and *realistic* by prioritizing research focus areas that are compelling and where significant progress will be made in the next decade.

This research strategy, summarized in Figure 5-2, is *comprehensive* in that it addresses all of the themes in Chapters 2, 3, and 4 and all of the funding agencies: the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Air Force Office of Scientific Research. In addition, this strategy has important international and cross-divisional contributions. In fact, the strategy is realized only through combined investments of these agencies in ground- and space-based observations, theory and modeling efforts, research and analysis, and development of the workforce to meet the broader needs of the field.

The strategy is *balanced* in that it includes research for the entire community to participate in shaping solar and space physics in the next decade. One common theme in both science and space weather research (Chapters 2 and 3) is that the local cosmos must be studied as a system, which requires the data from an integrated HelioSystems Laboratory (HSL) and the analysis and workforce development in DRIVE+.[2] While this theme is in common with both science and space weather, the other four themes in science and space weather carry equal weight in this balanced strategy. This balance is necessary to make significant progress on all science focus areas and achieve all space weather outcomes.

There are several critical elements to the strategy that are organized into three broad categories (Figure 5-2). The HSL and DRIVE+ are defined in Sections 5.2 and 5.3, respectively. DRIVE+ includes technology development that is needed for the assets in the next decade. Section 5.4 presents the preparation for beyond the next decade, including the technological and programmatic preparation that needs to occur in the next decade to prepare solar and space physics for beyond the end of the next decade. Chapter 6 includes the budget implications and decision rules for the research strategy and summarizes Chapter 5, including a summary of all recommendations in the report.

Figure 5-3 provides a timeline representation of the decadal research strategy, illustrating how the critical elements of the strategy are woven together to make significant science and space weather progress over the next decade. The figure also shows how existing programs are interleaved with new missions and programs. One new program is the flagship community science modeling program discussed in detail below. A major component of

[2] The 2013 decadal survey introduced the original Diversify, Realize, Integrate, Venture, Educate (DRIVE) initiative, a long-term framework for organizing and enhancing agency research programs that reflects the need for interagency cooperation. The recommended research strategy transforms DRIVE into DRIVE+ an includes recommended enhancements in supporting research and technology programs that are essential for realizing ambitious scientific progress.

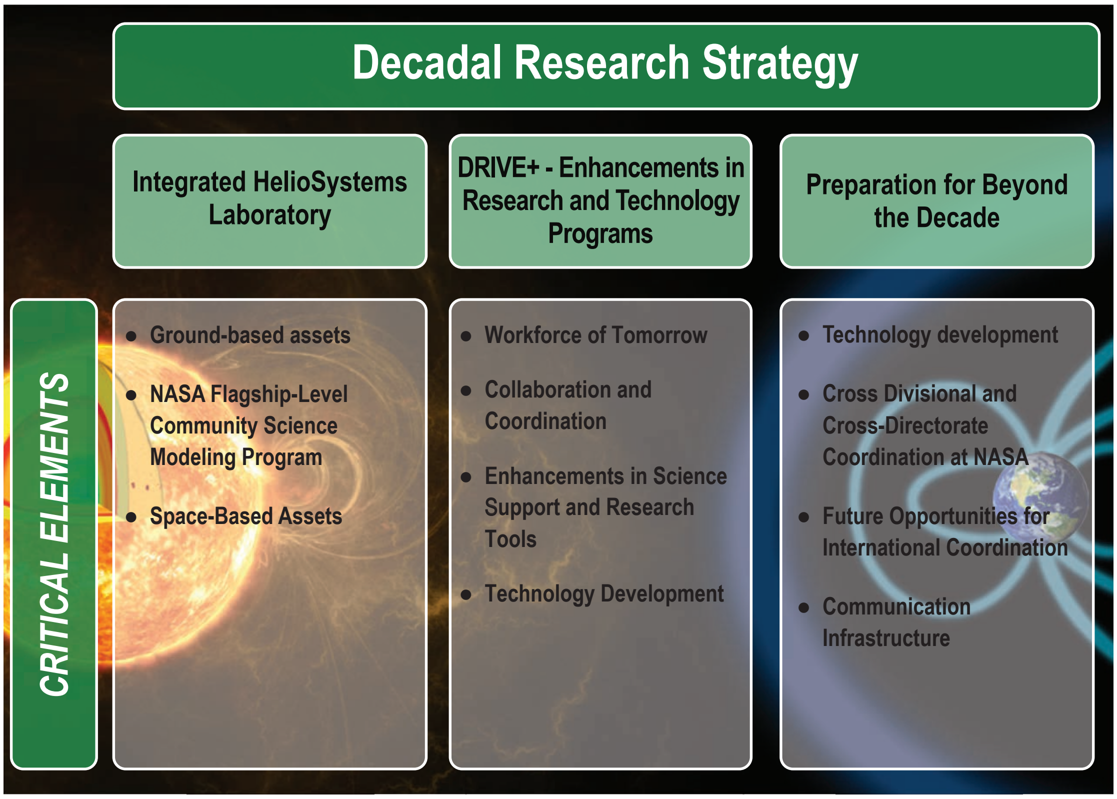

FIGURE 5-2 Critical elements of the comprehensive and balanced research strategy. These elements are organized into three broad categories: the integrated HelioSystems Laboratory, the Diversify, Realize, Integrate, Venture, Educate (DRIVE)+ programs, and preparation for beyond the next decade. These categories have some overlap—for example, technology development is important for the next decade (DRIVE+) and in preparation for beyond the decade. These categories are discussed in detail in Sections 5.2, 5.3, and 5.4, respectively.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Background elements from NASA/Goddard.

this strategy includes two discovery-enabling new NASA missions (see Figure 5-3). The new Solar Terrestrial Probes (STP) mission is represented by the notional Links mission, a groundbreaking combination of an in situ constellation and remote sensing imaging spacecraft of the highly structured magnetospheric and ionospheric plasmas in a heterogeneous constellation. This mission applies innovative technology to provide definitive answers to long-standing questions on global solar wind energy entry on the day side of the magnetosphere, and subsequent energy transport through the night side of the magnetosphere to the aurora and regions of large-scale currents. Furthermore, this mission determines the impacts that "intermediate-scale" or meso-scale processes have on the larger-scale evolution of the system. The answers and fundamental understandings from this mission are of high relevance for accurate and timely space weather predictions. The combined Geospace Dynamics Constellation (GDC) and Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC) missions (the high-priority missions from the 2013 solar and space physics decadal survey report [NRC 2013; hereafter "the 2013 decadal survey"] that are currently under development) act as a forerunner for technologies related to operating a heterogeneous constellation like the Links mission, where different spacecraft perform different observations.

The second discovery-enabling new NASA mission is a solar polar mission, represented by the notional Solar Polar Orbiter in the Living With a Star (LWS) program. This exploratory mission will, for the first time, measure magnetic fields and velocity structure for extended periods at the Sun's poles. These measurements are critical for understanding the origin of the solar magnetic dynamo and how the magnetic field drives solar activity and shapes the heliosphere over the course of the solar cycle. Understanding the polar fields and velocity structures is also a key factor in predicting space weather approaching Earth. Its vantage point enables comprehensive study of the creation and structuring of the solar corona and solar wind.

The research strategy timeline in Figure 5-3 also includes critical new ground elements—a new NSF Major Research Equipment and Facilities Construction (MREFC) project and two new NSF Mid-scale Research Infrastructure (MSRI) projects. The next-generation Global Oscillations Network Group (ngGONG) is the MREFC project in Figure 5-3 that is an enhanced successor to the National Solar Observatory's (NSO's) Global Oscillations Network Group (GONG) network. This comprehensive ground-based network is the first to include operational space weather requirements from its conception. The highest-priority, ground-based, mid-scale projects in Figure 5-3 are a MSRI-1 observing system simulation experiment (OSSE) study of Distributed Arrays of Small Heterogeneous Instruments (DASHI) and an MSRI-2 implementation of the Frequency-Agile Solar Radiotelescope (FASR). Both critical mid-scale projects perform important ionosphere–thermosphere–mesosphere (ITM), magnetospheric, and solar heliospheric science and broadly serve the ground-based solar and space physics community.

The missions and projects described above are key components of the integrated HSL. The full HSL takes advantage of these new missions and projects, HSL components already in operation, HSL components in development, and an enhanced model and simulation program within the HSL to achieve the ambitious and exciting science and space weather research described in Chapters 2 and 3. In this sense, the HSL is the ultimate resource, or laboratory, that the solar and space physics community uses to understand the complex and intertwined systems that make up the local cosmos. The HSL includes, but is distinct from, the NASA Heliophysics System Observatory (HSO) and relies on the integration within and across agencies and foundations to achieve this science and space weather research.

Significant progress on the *entirety* of the research guiding questions will not be possible without additions to this HSL, beyond the LWS and STP missions and the MREFC and MSRI projects described above. In particular, there is a growing need—driven in part by rapid advancements of spacecraft and instrument technologies—for a new NASA Explorer class that falls between the current Medium-Class Explorers (MIDEX) and larger-scale LWS and STP lines. To fill this mission cost gap and contribute to the balance of the overall research strategy, the decadal survey committee recommends establishing the Heliospheric Large Explorer (HeLEX) (see Section 5.2). HeLEXs are comparable to principal investigator (PI)-led New Frontiers missions in the NASA Planetary Science Division and expand the opportunities for PI-led scientific missions. The HeLEX class of missions would enable the realization of, for example, smaller-scale constellation missions, which have become increasingly important for studying the heliophysics system of systems.

There are a number of high-priority NASA missions whose development continues in the next decade and these missions are key elements of the research strategy. They include Explorer missions, the Interstellar Mapping and Acceleration Probe (IMAP), GDC, and DYNAMIC. As this decadal survey builds on the 2013 decadal survey that prioritized these missions, they contribute significantly to science progress and provide important balance to the overall research strategy in the next decade.

Space weather research in the next decade benefits from cross-agency coordination and collaboration as prescribed by the 2020 Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT Act; P.L. 116-181). This act outlines the space weather roles and responsibilities of the various agencies and the quad-agency memorandum of agreement, signed in 2023, among NASA, NSF, NOAA, and the Department of the Air Force, outlining opportunities for collaboration. The coordination groups around space weather (see Chapter 3 for details) are paving the way for efficient use of resources with increased scientific and societal impacts. For solar and space physics, such coordination and collaboration are major steps forward, and the space weather recommendations highlight some further steps that would continue the positive development.

Basic science research and technology development programs are the backbone of the research strategy. The 2013 decadal survey (NRC 2013) took an important step toward organizing research and technology programs with its recommendation of the DRIVE initiative. DRIVE continues to be a powerful organizational tool for research and technology programs into the next decade. It is multiagency, building on the strengths and investments of each agency, while reflecting the interagency cooperation needed to achieve decadal survey science goals. This decadal survey's research strategy for the next decade includes a transformation of DRIVE into DRIVE+ (Section 5.3). In Figure 5-3, DRIVE+ is part of the research strategy timeline. Where the integrated HSL provides all the data for

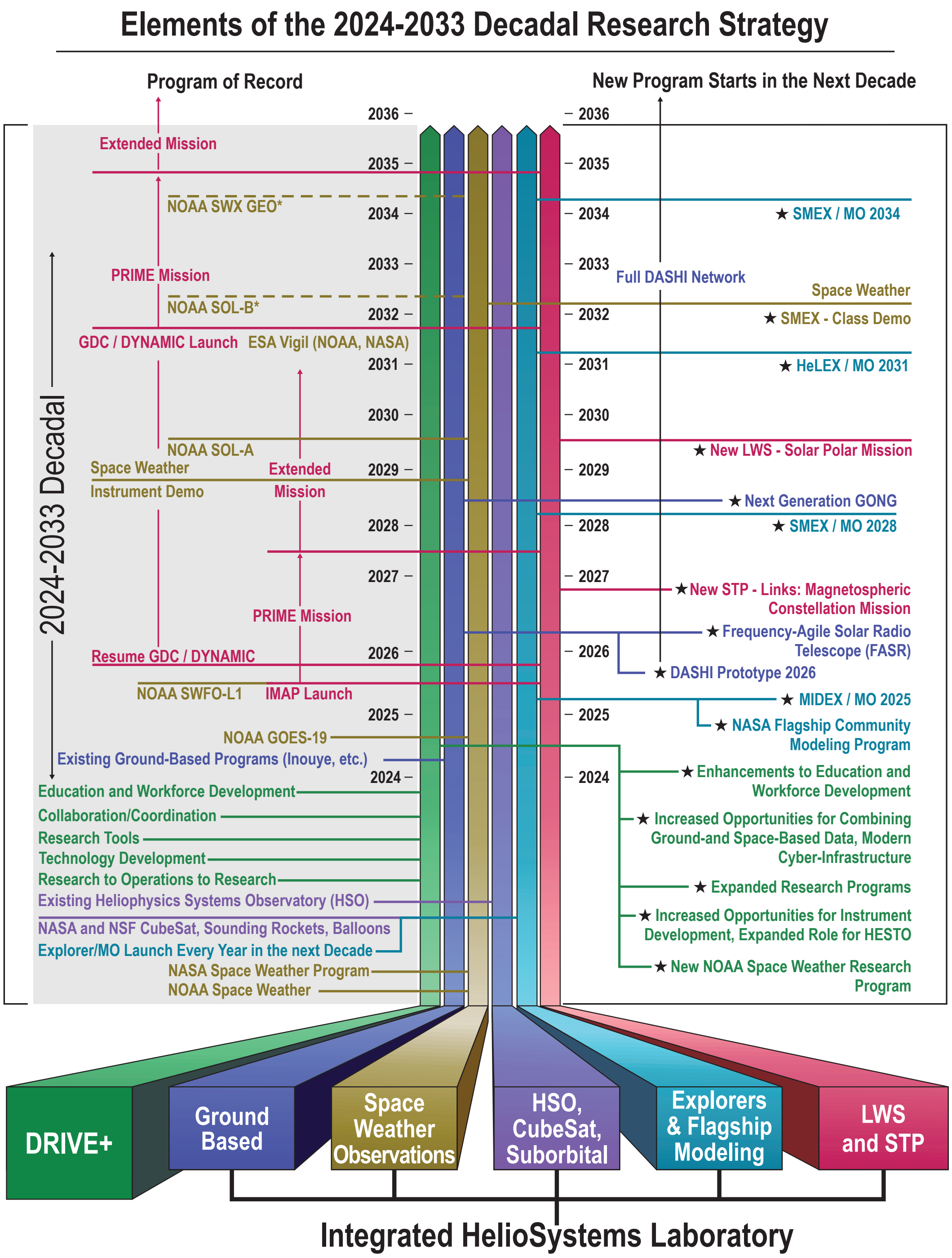

FIGURE 5-3 The timeline for realizing the ambitious and realistic research strategy. The HelioSystems Laboratory provides the observations and data, while DRIVE+ provides the underlying research needed to understand and assimilate the observations. The stars on the right-hand side of the timeline highlight new missions and programs recommended by this decadal survey.
NOTES: Acronyms provided in Appendix H. This figure was modified after release of the report to correct the NOAA space weather program of record.
SOURCE: Composed by AJ Galaviz III, Southwest Research Institute.

the science in the next decade, the science is accomplished through the vibrant research program that is DRIVE+. DRIVE+, like the integrated HSL, has existing elements as well as new enhancements in the research program for the next decade.

The research strategy extends beyond 2033, the end of the decadal survey interval. An important element of this strategy is the preparation for future decades (Section 5.4). This preparation includes developing new technologies and important interagency and international developments to pave the way for implementation of the inherently collaborative and international solar and space physics strategy beyond the next decade.

The investments that are needed to support the research strategy are described in Chapter 6.

5.2 AN INTEGRATED HELIOSYSTEMS LABORATORY

5.2.1 Introduction to the HelioSystems Laboratory[3]

The decadal science and space weather themes (Chapters 2 and 3) encompass scientific research that requires diverse sets of heterogeneous observations. However, the vastness of the local cosmos will always leave much of the space unobserved; thus system-level models are required to fill the gaps, provide the large-scale context, and bridge spatial and temporal scales. This section introduces the concept of an integrated HSL to describe all the missions, projects, and program elements that generate the data sets (from both observations and models) that are key to expanding the frontiers of solar and space physics and enabling significant progress across the broadest range of science and space weather themes.

There is already significant progress on these themes. For system science, NASA has moved toward managing its Heliophysics Division fleet as a coherent network, the HSO. The 2019 report *Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics: A Midterm Assessment* (NASEM 2020a) recommended that NSF and NASA coordinate their respective ground-based and space-based assets. The PROSWIFT Act codifies the space weather roles and interagency cooperation for NASA, NOAA, NSF, DoD, and the Department of the Interior (DOI). Notably, most of the NASA mission concepts submitted to this decadal survey (through community input papers) were constellation and/or remote sensing missions and, in many cases, these missions consisted of heterogeneous elements combining a variety of measurements from best-suited vantage points, including from the ground. Many of the concept ground-based facilities also consisted of distributed arrays of heterogeneous instrumentation or imaging arrays. There is a fundamental paradigm shift from individual spacecraft or ground-based facilities to heterogeneous constellations and integrated arrays of ground-based facilities that is emerging in solar and space physics for the next decade. Multiagency coordination between ground-based and space-based assets is needed to effectively achieve system science objectives.[4]

Solar and space physics is inherently transdisciplinary and requires a systems approach to understand the complex interactions between domains over a wide range of spatial and temporal scales. This necessitates comprehensive measurements around the globe, and from multiple vantage points in the space environment. Solar and space physics is therefore a global enterprise for which international collaboration is not just desirable, but necessary.

In the next decade, U.S. leadership in the international solar and space physics community requires development of diverse platforms of in situ and remote sensing instrumentation. This instrumentation must provide spatially distributed measurements with temporal continuity and integrated data processing. These measurements need to be supported by large-scale, system-level modeling to fully understand the diverse phenomena throughout our local cosmos. Integration of all solar and space physics ground-based and space-based assets is accomplished through NASA, NOAA, NSF, and Department of the Air Force–Air Force Office of Scientific Research (AFOSR) strategic science partnerships, complementing the space weather partnerships that have formed for coordination and collaboration on space weather research-to-operations-to-research programs. The vision for solar and space

[3] This section was modified after release of the report to correct agency responsibilities for ground-based infrastructure.

[4] This paragraph was modified after the release of the report to provide factual clarity regarding multiagency coordination for achieving the next decade's science goals.

physics for the next decade to discover the secrets of the local cosmos and to expand and safeguard humanity's home in space is realized with an integrated HSL, discussed below.

The collection of individual elements in the HSL described in this chapter is a "laboratory" in the broadest sense of the term, defined as a source of scientific and operational data. The laboratory is not confined to a specific type of element (e.g., a space-based mission or missions that would constitute an observatory). Rather, the HSL encompasses a wide range of elements that may be space-based, ground-based, or, analogous to the equipment (measuring devices, computers, etc.) used in a laboratory, theory and modeling. These assets are used both to conduct scientific experiments and to make space weather forecasts and predictions.

In this laboratory, the solar and space physics community conducts investigations into and makes predictions about *heliosystems*. This term is a shorthand for all the systems in the local cosmos, including the Sun, the heliosphere, and planetary magnetospheres, ionospheres, thermospheres, and mesospheres (including Earth's). The interplay within and among all these heliosystems and the comparison of these systems to other stellar systems is the essence of solar and space physics.

A key attribute of this laboratory is that it is *integrated*. A common scientific and space weather theme that prevails in this report (see Chapters 2 and 3) is the interconnectedness of all regions and entities under study. The next decade heralds a new era where the primary way to make progress on this common theme is to employ the assets of an integrated HSL.

Another key aspect of this integrated HSL is that major advances on critical science and space weather questions will require missions or combinations of missions that provide large-scale, heterogeneous constellation measurements, measurements from both the ground and space, and measurements within and away from the Sun–Earth line. In the next decade, single- and multiple-spacecraft missions will continue to provide critical observations to answer targeted questions—for example, in science theme 2, A Laboratory in Space; Building Blocks of Understanding. At the same time, these missions will add to the heterogeneous measurements of the HSL. Thus, missions will have a dual nature where they address fundamental science and at the same time add to the system. Also in the next decade, the Sun–Earth line will continue to be an important vantage point to explore and diagnose the Sun–Earth system. However, other vantage points have grown in importance as necessary for a full understanding of the dynamics of the Sun and the space between it and Earth.

An underexploited dimension to international science collaborations is to leverage extant ground- and space-based instruments to jointly attack problems of interest. Such efforts require close cooperation and coordination. Examples include the Whole Sun Month (Biesecker et al. 1999), the Whole Heliosphere Interval (Woods et al. 2009), and the Whole Heliosphere and Planetary Interactions international campaigns (Gibson et al. 2023; UCAR 2024). These efforts have been largely voluntary with limited resources available at the institutional or agency level. The development of tools to enable coordinated observations, coordinated data analysis, and data sharing between international partners would facilitate such collaborations.

Increasing the lead time and accuracy of space weather predictions requires monitoring the Sun and solar wind with ecliptic and off-ecliptic vantage points, each having their own benefits. Collaboration with the European Space Agency (ESA) on the Vigil mission provides an opportunity to demonstrate the capabilities of solar and solar wind monitoring from what will be a novel vantage point in the ecliptic, but away from the Sun–Earth line. (See also Section 5.2.3.) Vigil's operational demonstration supports the NASA Artemis Moon to Mars initiative, which requires monitoring the inner heliosphere over a wide range of solar longitudes as the relative positions of Earth and Mars vary over time. The collaboration with ESA also underscores the important role that international collaboration plays in the integrated HSL.

Conclusion: Achieving the vision for solar and space physics and realizing the research strategy requires significantly enhanced communication within and across the funding agencies. Meeting the diverse observational (both ground-based and space-based) and modeling needs is achieved only through an interagency strategic planning activity. Such planning would allow evaluation of missions and projects based solely on traceable implementation plans and ensure that the needs of all agencies are addressed, from fundamental science to space weather research and applications. Lastly, an interagency strategy would foster coordinated use of resources across agencies without explicit community direction in each case.

Recommendation 5-1: The National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the National Oceanic and Atmospheric Administration (NOAA) should address the science and space weather goals of the decadal survey by managing space-based missions and ground-based instruments within the context of an integrated HelioSystems Laboratory (HSL). The HSL would include the NASA missions that comprise the Heliophysics System Observatory (HSO), NSF-funded ground-based instruments, NOAA space-based assets, and flagship-level theory and modeling, which all work together in concert to provide data for scientific and space weather research.

Specific recommendations for elements of the HSL are as follows:

- **NASA, NSF, and NOAA should create an HSL working group to develop tools and standards for the scientific community to coordinate joint observations of NASA, NSF, NOAA, and international assets. The goal is to encourage joint observing campaigns by making collaboration easier.**
- **NASA should manage the HSO as a strategic network of all current and planned missions, with regular assessments of contributions from international missions and NASA missions in their prime phase, and potential contributions from planned missions. For missions in the extended phase, NASA should determine how the senior review and infrastructure mission evaluations fit into a strategic framework that emphasizes system-level coherence.**
- **NASA should organize a tactical HSO working group, with membership from HSO mission teams, to coordinate observations and maximize the scientific return of the HSO.**
- **Early in the pre-formulation phase of each new space mission, NSF, NASA, and NOAA, possibly in collaboration with international partners, should hold strategic discussions about potential contributed ground-based components that could enhance the science return.[5]**
- **NSF should conduct regular portfolio reviews and consider the current and potential roles of ground-based instruments relevant to the HSL during these reviews. Renewal or recompetition of continuing operations of existing instruments should include consideration of their contributions to the HSL.**
- **To contribute to the HSL, NOAA should make the data from its missions fully accessible and useable for scientific research.**

The creation of an HSL working group would benefit from community input and involvement. This working group would enable the agencies to facilitate coordination within the scientific community to increase synergy and overall science return. The emphasis of this working group would be on coordination and information transfer among the HSL elements. Some of the tools developed by this working group would enable the creation of top-level observing timelines for multimission, multiobservatory campaigns and the sharing of details of each asset's contribution to the joint endeavor. The working group would also facilitate international cooperation by providing a single entity to engage the international science and space weather communities.

The recommendation on HSO strategic management is in line with the report *The 2023 Senior Review of the Heliophysics System Observatory Missions* (NASA 2023b). The senior review panel suggested that NASA "develop opportunities for HSO science working groups." However, Recommendation 5-1 goes beyond the senior review panel suggestion by incorporation into the broader HSL. These working groups ultimately would be coordinated through the HSL working group and provide opportunities to focus on a richer mission and project portfolio outside of the HSO.

[5] This language was changed following the release of the report to clarify the roles of the agencies to which this recommendation is directed.

The 2020 senior review introduced process and policy changes that included creating a new infrastructure category of missions. Following the 2023 senior review, four projects were approved for extended missions that included science investigations. Nine projects were approved for operations funding, without project-funded science investigations (i.e., designated as infrastructure). This included three that were already in the infrastructure category (Luce 2023).

The purpose of the infrastructure category and the process used for transitioning missions was not clearly communicated to the community. In response to questions submitted by the decadal survey committee, NASA stated, “the changes implemented in Senior Reviews 2020 and 2023 were driven by program management goals and budget realities.” While NASA goals include “ensuring the availability and usability of high-value data products and integrating the HSO projects into Division strategic efforts,” the criteria used for decision-making have not been clearly articulated. It may be beneficial to transition missions whose main contributions are the collection of data in strategic regions as part of the HSO (e.g., solar wind measurements) in that it lessens the burden of the senior review process. For other missions, science investigations often lead to innovative approaches (e.g., The Time History of Events and Macroscale Interactions during Substorms [THEMIS] mission spawned a new mission, Acceleration, Reconnection, Turbulence and Electrodynamics of Moon’s Interaction with the Sun [ARTEMIS] when it moved two of its spacecraft to the Moon), coordinated data collection (e.g., special modes during special scientific opportunities like an eclipse, and fortuitous conjunctions with other spacecraft), and scientific data validation by experts familiar with the instruments. Moving missions to infrastructure prematurely could have adverse impacts on the quality of data collected.

Conclusion: The decadal survey committee is concerned about the decision-making process for moving missions to the infrastructure category. The criteria for transitioning missions in the previous senior review did not appear to be based on developing a coherent program. It is critical that NASA understand how the senior review of the HSO, especially the process of moving missions to infrastructure status, impacts the operation of the HSO as an essential component of the HSL.

The elements of the integrated HSL are illustrated schematically in Figure 5-3. Each HSL element is comprised of several parts and there are several groups within these parts (Table 5-1). Each element of the HSL fulfills a specific role in the research strategy and thereby comes with recommendations for the next decade. The research needs and recommendations are discussed below.

TABLE 5-1 Elements in the Integrated HelioSystems Laboratory

Assets in the Integrated HelioSystems Laboratory	
Ground-based assets and community modeling	NSF ground-based projects
	NOAA and NSF ground-based infrastructure for space weather
Theory and modeling	NASA flagship community science modeling program
Space-based and suborbital assets	NASA and NSF CubeSats
	NASA suborbital program (sounding rockets and balloons)
	NASA Heliophysics Explorers
	NOAA space weather observations
	NASA Space Weather program
	NASA Heliophysics System Observatory

NOTE: This table was updated after the release of the report to correct ground-based assets.

5.2.2 Ground-Based Assets in the Integrated HelioSystems Laboratory[6]

NSF Ground-Based Instrumentation and Facilities

NSF funds a wide range of ground-based facilities and programs that support solar and space physics research. Some of the major ground-based facilities are shown in Figure 5-4. One of these facilities is the Daniel K. Inouye Solar Telescope, which commenced science operations in 2022 and is managed by the NSO. There are plans for continued instrument development for Inouye as part of the NSO cooperative agreement with the NSF. This ongoing instrument development is critical to insure continued scientific productivity and leadership.

NSF funds national centers that support solar and space physics observations (e.g., the National Center for Atmospheric Research [NCAR] High Altitude Observatory [HAO], NSO, and the National Radio Astronomy Observatory [NRAO]), as well as many smaller facilities. Many processes, particularly in the upper atmosphere occur over a broad spatial scale. Thus, their study calls for coordination of both existing NSF assets and future investments. An example where NSF stepped in to facilitate coordination of independent ground-based measurements is the SuperDARN global radar network. A separate example of NSF coordination of spaced-based measurements is the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) field-aligned current measurements.[7]

The locations of the ground-based facilities (Figure 5-4) underscore the strong international collaboration that exists between NSF and other agencies. NSF currently supports U.S. partnerships in incoherent scatter radars (AMISRs and Jicamarca in Figure 5-4) and worldwide networks such as SuperDARN and GONG (also in Figure 5-4). The NSF collaborations also enable the aggregation and dissemination of data from a ground-based network of magnetometers distributed around the globe (SuperMAG). NSF's international engagement extends to 20 nations located in the Americas, Asia, Europe, and Africa.

The system science central to the next decade emphasizes the need to build on existing NSF assets. The NSF portfolio review process (Recommendation 5-1) is important for identifying upgrades and continued operation of these existing assets. These existing facilities are important for the collaboration between ground-based projects and space-based missions in the next decade. The community input papers submitted to the survey also revealed a strong need for mid-scale ground-based research infrastructure and include many concepts for novel, exciting, and timely ground-based instruments and facilities. The mid-scale projects represent a vibrant innovation space that address frontier science priorities both as standalone investigations and as important components of an integrated HSL.

Until recently, the NSF funding opportunities included a significant gap between Major Research Infrastructure (MRI; capped at $4 million) and the MREFC ($100 million and above) funding opportunities. NSF responded by introducing the MSRI program in 2016 as one of its 10 "Big Ideas." NSF defines research infrastructure as any combination of facilities, equipment, instrumentation, or computational hardware or software, and the necessary human capital in support of the same. The MSRI program is divided into two tracks: MSRI-1 supports both research infrastructure design projects and implementation projects. For design projects, the cost range is $400,000 to $20 million; for implementation projects, the range is $4 million to $20 million. MSRI-2 supports research infrastructure implementation projects with a total cost in the range of $20 million to $100 million. The first call for the MSRI was in 2019, with opportunities recurring every 2 years. The decadal survey committee has identified two priority mid-scale projects for this new funding program. These projects are important elements of the ground-based part of the HSL.

The priority MSRI-2 project is FASR, a solar radiotelescope that was a top priority of the 2003 and 2013 solar and space physics decadal surveys (NRC 2003 and NASEM 2013, respectively), was identified by the 2010 astronomy and astrophysics decadal survey as "doable now" (NRC 2010), and by the 2020 astronomy and astrophysics decadal survey as "a missed opportunity" (NASEM 2023). FASR is first and foremost a basic research instrument that opens a new window onto fundamental processes on the Sun. FASR images the solar atmosphere in

[6] This section was modified after release of the report to correct agency responsibilities for ground-based infrastructure.

[7] Although AMPERE measurements are from a space-based data buy, it is included here because NSF has supported its coordination and implementation for many years.

FIGURE 5-4 Major ground-based facilities either developed by the National Science Foundation (NSF) or with substantial NSF support. The blue dots represent incoherent scatter radars (Advanced Modular Incoherent Scatter Radar [AMISR], Poker Flat Incoherent Scatter Radar [PFISR], Jicamarca Radio Observatory, Millstone Hill Radar); the black dots represent Super Dual Auroral Radar Network (SuperDARN) sites; the red dots represent radio observatories (Atacama Large Millimeter/submillimeter Array [ALMA], Green Bank Telescope [GBT], Very Large Array [VLA], Expanded Owens Valley Solar Array [EOVSA]); the yellow dots represent optical observatories (GONG, Mauna Loa Solar Observatory [MLSO], Daniel K. Inouye Solar Telescope [Inouye]); and the orange square represents the High-frequency Active Auroral Research Program (HAARP).
SOURCES: (*Inouye*) NSO/AURA/NSF, https://nso.edu/gallery/gallery-dkist/#foogallery-50374/i:12. CC BY 4.0; (*EOVSA*) Courtesy of Dale Gary, NJIT; (*Jicamarca*) Woodman et al. (2019), https://doi.org/10.5194/hgss-10-245-2019. CC BY 4.0; (*RISR-N*) Reprinted with permission from T. Valentic, J. Buonocore, M. Cousins, et al., 2013, "AMISR the Advanced Modular Incoherent Scatter Radar," Pp. 659–663 in 2013 IEEE International Symposium on Phased Array Systems and Technology, https://doi.org/10.1109/ARRAY.2013.6731908. Copyright © 2013, IEEE; (*SuperDARN*) NSF/USAP/Peter Rejcek; (*GONG*) GONG/NSO/AURA/NSF, https://nso.edu/telescopes/nisp/gong. CC BY 4.0; (*ALMA*) NRAO/AUI/NSF, "ALMA Background 7," https://public.nrao.edu/gallery/alma-background-7. CC BY 3.0.

three-dimensional (3D) at radio wavelengths (frequencies from 200 MHz to 20 GHz) from the midchromosphere up into the midcorona with a high degree of angular (1″ at 20 GHz) and temporal resolution (as high as 20 ms). This innovative array (Figure 5-5) measures the plasma state of the solar atmosphere in less than 1 second (snapshot imaging) with a high degree of fidelity and dynamic range.

The unique characteristic of FASR is its ability to make quantitative measurements of chromospheric and coronal magnetic fields, both on the disk and above the limb, in both quiescent plasma and in energetic and dynamic phenomena such as flares and coronal mass ejections (CMEs) and to measure the spatiotemporal evolution of the electron distribution function for both quiescent and explosive phenomena. As a 3D "camera," FASR will observe the Sun's atmosphere as a coupled system, providing entirely new perspectives on its role as the central driver of heliosystems.

FIGURE 5-5 A rendering of Frequency-Agile Solar Radiotelescope antennas. The two antenna subsystems provide imaging and spectroscopy over two radio broad frequency ranges.
SOURCE: S. Yu, New Jersey Institute of Technology.

The Expanded Owens Valley Solar Array (EOVSA), an array of 13 antennas, has served as the FASR pathfinder and science testbed since 2017. All significant technical risks have been retired; procedures to calibrate, archive, and disseminate data using automatic processing have been developed; and strategies to address key science objectives have been determined. FASR is ready to proceed to the development of the project execution plan and to implementation immediately. Cost estimates place FASR within the MSRI-2 line.

Conclusion: There has been a longstanding need to exploit imaging and spectroscopy over a broad range of radio wavelengths to take advantage of unique and complementary diagnostics of the plasma state and plasma processes in the Sun's atmosphere and to observe them as a system from the chromosphere to the midcorona. As a high-performance radio array designed to perform ultra-broadband imaging spectropolarimetry at radio wavelengths, FASR fulfills this need.

The priority MSRI-1 project is DASHI, which targets the ITM DASHI concept goals and magnetosphere distributed network goals. This mid-scale concept was recognized by both the 2003 and 2013 decadal surveys (NASEM 2013; NRC 2003) and the 2015 Space Weather Action Plan (NSTC 2015a). DASHI greatly extends the spatial coverage of current ground-based sensor arrays spanning North and South America, transforming present-day, ad hoc sensing approaches into a strategically planned network needed for carrying out a diverse set of system science investigations. DASHI provides continuous distributed observations of key state parameters of the upper atmosphere, including plasma and neutral density, composition, temperature, and electrodynamic parameters from about 80 to 400 km altitude.

The unique ability of DASHI is that its concerted observations allow resolution of spatio-temporal couplings in multiple scales, which enables transformative advances in understanding the coupled mesosphere–thermosphere–ionosphere–magnetosphere system. Such a system is needed to provide the upper atmosphere linkages and feedback processes to the magnetospheric mesoscale dynamics, which is recognized as a key research area for the next decade. The unique ability of DASHI to resolve vertical, horizontal, and temporal variations makes it a highly valuable tool for space weather by providing input into comprehensive nowcasting and forecasting models.

The DASHI concept builds on observing stations that are distributed geographically and host an array of different instruments. When combined, this instrumentation provides simultaneous measurements covering wide areas. The instruments may include scanning Doppler imagers, Fabry-Pérot interferometers, all-sky imagers, global navigation satellite system (GNSS) receivers, meteor radars, magnetometers, ionosondes, and other instrumentation. DASHI complements the incoherent and coherent scatter radars (the existing and planned various incoherent scatter radars and the SuperDARN network). Because most of the instruments have been successfully deployed before, the concept is technologically mature.

The DASHI concept could be realized in multiple ways in terms of number and location of observing sites as well as the instrumentation. Several implementation options were described by the decadal survey panels. It is clear that a comprehensive network, such as that illustrated in Figure 5-6, is well beyond the Distributed Array of Small Instruments (DASI) in number and complexity of the instrumentation. However, OSSE modeling studies are needed to determine the optimal number and location of the DASHI sites in terms of balance between observing requirements that are tied to science objectives and available resources, including the cyber-infrastructure needed to support scientific use and interactions between the DASHI sites. The completed OSSE, followed by deployment of prototype instrument arrays, will yield a cost estimate that determines whether a full-scale DASHI is realized

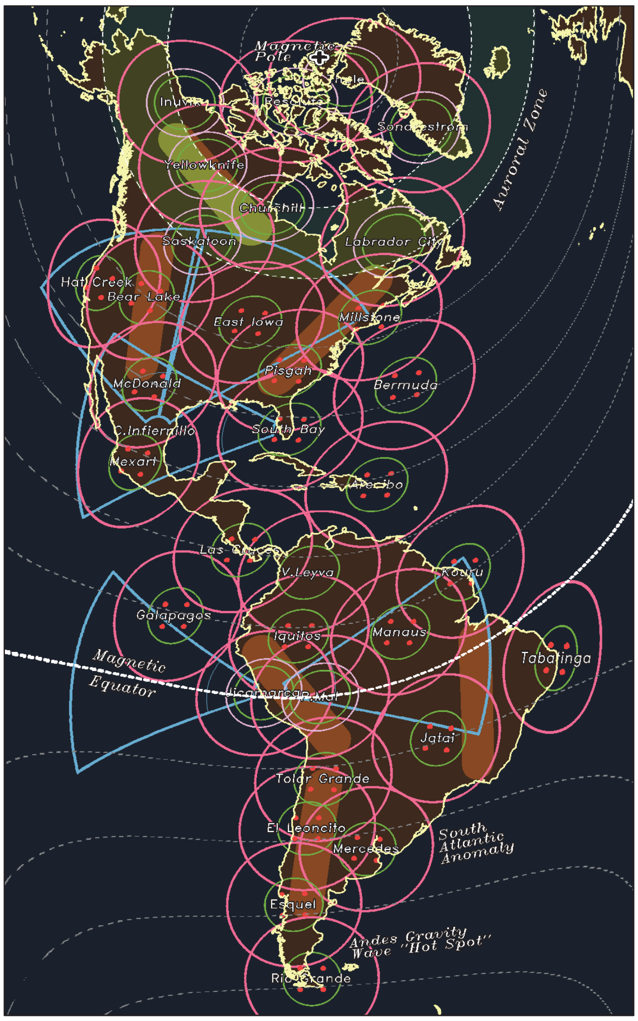

FIGURE 5-6 A conceptual distribution of a heterogeneous array of instruments with existing instruments such as Super Dual Auroral Radar Network (SuperDARN) and the coverage they provide.
SOURCE: Conde et al. (2022), https://doi.org/10.3847/25c2cfeb.593c3238. CC BY 4.0.

through the NSF MSRI-2 or the MREFC line. The OSSE and associated planning and prototyping activities are a good match to the MSRI-1 track.

Conclusion: DASHI combines new and existing resources to create a distributed array for the NSF geospace community to enable a transformative systems science approach to mesosphere–thermosphere–ionosphere–magnetosphere coupling. Before full implementation, the DASHI concept requires OSSE modeling studies to determine the optimal number and location of DASHI sites and their optimal instrumentation to maximize the ITM and magnetospheric science return, as well as associated planning and prototyping activities to determine the cost.

The combined FASR and DASHI high-priority projects benefit both the solar and geospace communities. In fact, the combined projects constitute a strategic plan for convergent research that crosses the NSF Mathematical and Physical Sciences (MPS) and Geosciences (GEO) directorates. Furthermore, these two projects contribute to space weather research. As such, this plan for the MPS and GEO communities is synergistic with recommendations to better coordinate solar, geospace, and space weather research at NSF.

Recommendation 5-2: The highest priorities for the National Science Foundation's Mid-scale Research Infrastructure (MSRI) programs are to

- **Develop the project execution plan for the Frequency Agile Solar Radiotelescope (FASR) and proceed to implementation as a MSRI-2 project; and**
- **Develop and deploy a prototype Distributed Array of Scientific Heterogeneous Instruments (DASHI) as a MSRI-1 project that includes an observing system simulation experiment and a cost estimate for a full-scale DASHI.**

The ground-based projects in Recommendations 5-2 and 5-3 are those that best contribute to the comprehensive, balanced research strategy. Other high-priority projects considered for the various NSF programs are listed in Table 5-2 in alphabetical, but not in priority, order.

While there is keen interest in mid-scale infrastructure, larger investments in ground-based infrastructure in support of solar and space physics are also needed. The ngGONG (Figure 5-7) is a modern and enhanced successor to the NSO's GONG network. Originally deployed in 1995, GONG was designed to explore the Sun's interior using helioseismology with homogeneous instrumentation on six sites distributed around the globe to provide continuous observations of the Sun. The network was later enhanced to make Hα observations. GONG has also become a valuable space-weather asset, as the project has made magnetograms and far-side images available.

Now approaching 30 years of service, GONG is an aging infrastructure that is difficult to maintain and operate. Yet, its measurements have become more important than ever before, both for scientific research and space weather operations. These important measurements will be extended by ngGONG. For scientific research, ngGONG will continue and expand critical measurements on the Sun–Earth line complementing the space-based observations, enabling more comprehensive study of the Sun's interior, the nature of the solar magnetic dynamo, and mapping solar activity on the far-side of the Sun. For space weather operations, ngGONG will continue to be a critical part of the infrastructure for space weather operations.

The ngGONG facility will be the first ground-based network that includes operational space weather requirements from its conception. Cost estimates suggest that ngGONG is appropriate for development and deployment under the NSF MREFC line. However, as a facility that plays a role in both research and space weather operations, and because it is inherently international in nature, ngGONG requires collaboration with NOAA, DAF-AFOSR, and international partners such as the European counterpart to ngGONG, the Solar Physics Research Integrated Network Group (SPRING) of the SOLARNET project.

Conclusion: With its combined science and space weather operations mission, ngGONG is an example of a facility with dual purpose in the integrated HSL.

TABLE 5-2 Other Priority Ground-Based and Other National Science Foundation (NSF)-Funded Projects Listed in Alphabetical Order and Not Priority Order

NSF-Funded Asset	Primary Measurement	Discipline	Purpose/Need
Active Magnetosphere and Planetary Electrodynamics Response Experiment/ Iridium-NEXT (AMPERE-Next)	Magnetic field	Magnetosphere	The AMPERE project uses magnetometer recordings from operational Iridium satellites to deduce the large-scale field-aligned current pattern coupling the magnetosphere and ionosphere. The second-generation Iridium-NEXT spacecraft have been launched, and the new data products first available in 2022, AMPERE-Next needs further investments in ground-processing and operations infrastructure to enhance system state determination and now-casting capabilities.
Coronal Solar Magnetism Observatory (COSMO)	Magnetic field	Solar-Heliosphere	The dynamical evolution and reconfiguration of the magnetic field in the solar atmosphere are critical processes that underlie a host of outstanding problems concerning the corona and solar wind, and impulsive energy release in flares and eruptions. The central component of COSMO is a 1.5 m refractive coronagraph observing in multiple spectral lines to establish the density and line-of-sight velocity in the plane of the sky as well as the orientation of the coronal magnetic field. It is anticipated that the coronal magnetic field along the line-of-sight is also measured via the Zeeman effect. The coronagraph is complemented by a full-disk/limb-imaging spectropolarimeter (Community Synoptic Chromospheric Magnetograph [ChroMag]) and a white light coronagraph (COSMO K-coronagraph [K-Cor]).
Extended GNSS Network	Total electron content and scintillation	Ionosphere–Thermosphere–Mesosphere	Total electron content and scintillation measurements are used to characterize the ionosphere on horizontal scales of ~100 km. These measurements are both scientifically significant and critically important for space weather predictions for ground-satellite and other high-frequency communications. Upgrades are needed to existing surface-based GNSS receiver infrastructure as well as expansion into low-latitude coverage oceanic and the African regions, and to provide operational support to exploit these data more fully for space weather operations and assimilative modeling.
Light Detection and Ranging (LiDAR)	Altitude profiles of neutral atmosphere parameters	Ionosphere–Thermosphere–Mesosphere	LiDARs provide altitude resolved thermospheric temperatures, composition and winds. A new, high-power aperture LiDAR facility capable of providing continuous altitude profiles of the upper atmosphere fills an important altitude gap in these measurements.
Meteor Radar Network		Ionosphere–Thermosphere–Mesosphere	Meteor radar networks measure neutral winds in the upper atmosphere and provide key insights into tidal and planetary wave activity. A global network is needed for whole-atmosphere modeling and studies of gravity waves. It has been identified as critical ground-based infrastructure to characterize the global distribution and variability of wind and gravity waves.

TABLE 5-2 Continued

NSF-Funded Asset	Primary Measurement	Discipline	Purpose/Need
Midlatitude or Subauroral Incoherent Scatter Radar (IS-Radar)		Ionosphere–Thermosphere–Mesosphere and Magnetosphere	A modern midlatitude/subauroral IS-Radar is needed to remotely sense the dynamics of the inner magnetosphere. It would complement Advanced Modular Incoherent Scatter Radar (AMISRs), provide ionosphere-to-magnetosphere convection comparisons with magnetospheric missions and complement DASHI.
Poker Flat/Resolute Bay IS-Radar refurbishment		Ionosphere–Thermosphere–Mesosphere and Magnetosphere	The AMISR network comprising three stations—Poker Flat Incoherent Scatter Radar (PFISR), Resolute Bay Incoherent Scatter Radar-North (RISR-N), and RISR-Canada (RISR-C)—provides comprehensive measurements of ionospheric parameters for study of magnetosphere–ionosphere–thermosphere–mesosphere coupling. Having operated more than a decade, both NSF stations need refurbishment of the antenna elements. The PFISR facility is critical for the success of the high-latitude sounding rocket program, because it aids in launch conditions and crucial contextual measurements for auroral, neutral atmosphere, and electrodynamic missions (e.g., Geospace Dynamics Constellation [GDC] and Dynamical Neutral Atmosphere-Ionosphere Coupling [DYNAMIC]).
Super Dual Auroral Radar Network (SuperDARN) Network	Ionospheric flows	Ionosphere–Thermosphere–Mesosphere and Magnetosphere	Auroral radar network to make multiscale measurements of ionospheric flows in both the northern and southern hemisphere, critical for quantifying the relative importance of electric field variations on various scales for energy deposition rates. Continuing support of U.S.-led dual auroral radars and their participation in the international SuperDARN consortium is needed, as are upgrades to in hardware and software to improve station imaging capabilities.

Recommendation 5-3: The highest-priority large Major Research Equipment and Facilities Construction-scale project for the National Science Foundation for the next decade is the Next Generation Global Oscillations Network Group (ngGONG). In light of its importance to space weather, the development, implementation, and operation of ngGONG should be supported through partnerships with the National Oceanic and Atmospheric Administration, the Department of Defense-Air Force Office of Scientific Research, and international partners.

Table 5-3 summarizes mid-scale and large investments projects considered by the three science panels and prioritized by the steering committee.

In the next decade, the NSF contributions to space weather will increase significantly. Several of the existing and future NSF facilities support and provide key data for space weather observations (see Table 5-4). To integrate these increased contributions into NSF and into the national space weather endeavor, NSF needs an agencywide plan. The recommendation that NSF develop this agencywide strategic space weather plan is in Chapter 3 (see Recommendation 3-1).

Ground-Based Infrastructure for Space Weather

Ground-based infrastructure provides valuable information for space weather with importance to both predictions and monitoring of the current state of the system. Similar to their space-based counterparts, ground-based

FIGURE 5-7 Concept of a Next Generation Global Oscillations Network Group (ngGONG) site. The telescope would be mounted on a pier to reduce ground-layer seeing.
SOURCE: Hill et al. (2019), https://baas.aas.org/pub/2020n7i074/release/1. CC BY 4.0.

space weather assets range from dedicated operational monitoring systems, controlled by a variety of organizations to science instrumentation, which also serves as a source of space weather information. An example of such dual use is the solar monitoring provided by ngGONG (see the discussion above and Table 5-4). In the next decade, the synergy between NOAA and other agencies will be expanded and enhanced. For both ground- and space-based data, the use of NOAA data in scientific research and the use of scientific data in NOAA research will be key to advancing the research strategy. For NOAA, Recommendation 3-7 (see Chapter 3, Section 3.3.5) states that the agency should take advantage of new data opportunities by assessing the value of new data streams. This recommendation includes both ground-based and space-based data streams.

Ground-based space weather assets are not limited to the NSF assets in Table 5-4. The U.S. Air Force 557th Weather Wing has the responsibility for providing space weather information to all DoD services worldwide, which it does by operating the Space Weather Operation Center and by providing data to NOAA Space Weather Prediction Center (SWPC). Data from the Solar Electro-Optical Network (SEON) and Radio Solar Telescope Network (RSTN) are publicly available but not all other data are accessible. To maximize the potential of these space weather assets, they need to be integrated and managed strategically, and made publicly accessible. The PROSWIFT Act provides some guidance by identifying which agencies are responsible for which assets.

TABLE 5-3 Summary of the Highest-Priority Ground-Based Projects for the National Science Foundation Programs

Program	Ground-Based Project
Mid-scale (MSRI-1)	OSSE study of Distributed Arrays of Small Heterogeneous Instruments (DASHI)
Mid-scale (MSRI-2)	Implementation of the Frequency-Agile Solar Radiotelescope (FASR)
Large	Next Generation Global Oscillations Network Group (ngGONG)

NOTE: MSRI, Mid-scale Research Infrastructure; OSSE, observing system simulation experiment.

TABLE 5-4 Examples of Existing and Planned National Science Foundation–Supported Ground-Based Instrumentation with Potential for Providing Space Weather Information

	Instrument/Project		
	Existing	Future	Space Weather Capability
Solar	GONG	ngGONG	Vector B field in the photosphere and chromosphere
		FASR	Three-dimensional plasma state including B field from chromosphere to corona; shocks and energetic electrons
Magnetosphere	AMPERE	AMPERE-Next	Field-aligned currents in the ionosphere
		DASHI	Ionospheric parameters and ground magnetic variations
			Ionospheric scintillations
Ionosphere	Incoherent scatter radars	GNSS Network	Total electron content and scintillation measurements
		LiDAR Facility	Neutral winds, temperature, and composition
		Meteor Radar Network	Neutral winds
		Midlatitude, PFISR/RISR/ Sub-Auroral	Ionospheric electron density, electron temperature, ion temperature, line-of-sight ion velocity
	SuperDARN		Ionospheric convection
		DASHI	Ionospheric parameters and ground magnetic variations

NOTE: AMPERE, Active Magnetosphere and Planetary Electrodynamics Response Experiment; DASHI, Distributed Arrays of Small Heterogeneous Instruments; FASR, Frequency Agile Solar Radiotelescope; GNSS, Global Navigation Satellite System; GONG, Global Oscillation Network Group; LiDAR, light detection and ranging; ngGONG, Next Generation Global Oscillations Network Group; PFISR, Poker Flat Incoherent Scatter Radar; RISR, Resolute Bay Incoherent Scatter Radar; SuperDARN, Super Dual Auroral Radar Network.

NASA Flagship-Level Community Science Modeling Program

Space- and ground-based observations and theory and modeling form a triad for discovery in solar and space physics. In the past decade, physics-based models have made great strides in delivering scientific breakthroughs, explaining data from existing assets, motivating new missions, and furthering the national space weather enterprise. These advances were achieved with relatively modest investment by the funding agencies via a hierarchy of programs (see Section 5.3) ranging from regular grants to large-scale programs such as the recent NASA Space Weather Centers of Excellence and DRIVE Science Centers (DSCs; see Section 5.3). The past decade's advances brought the field to a state where the current funding paradigm no longer meets future challenges. These challenges include ever-increasing physical complexity of the models, the emerging paradigm of model-data fusion, using artificial intelligence (AI) for data assimilation, rapid development of the high-performance computing (HPC) landscape and the need to adhere to open science standards. Simply put, developing and maintaining complex community models has become as expensive as building and operating space missions or major ground-based facilities.[8]

To make progress in solar and space physics, the heliosphere and the heliosystems comprising it need to be treated as complex systems composed of several interacting components. These interactions occur across vast ranges of spatial and temporal scales, from the electron micro-scales to the global scales of the entire system.

[8] For reference, a large part of the NCAR annual budget of $100 million goes toward supporting community Earth system modeling (Slingo et al. 2022). The UK meteorological office is procuring more than $1 billion over the next decade for the hardware required to support climate modeling (e.g., https://www.hpcwire.com/2021/05/13/behind-the-met-offices-procurement-of-a-billion-dollar-microsoft-system).

Numerical simulations of such systems require developing highly complex models that encapsulate different physical regimes, couple disparate spatial regions, and cover an enormous range of length scales. The challenge is analogous to simulations of fusion devices, nuclear reactors, or numerical prediction of weather and climate. A good example of a complex community model with sustained infrastructure is the Community Earth System Model (CESM). This model was developed for climate prediction by the National Center for Atmospheric Research (NCAR) in collaboration with the larger research community.

State-of-the art solar and space physics models already push the boundaries of physical and algorithmical complexity. However, modeling efforts by individual groups are hampered by a lack of sustained infrastructure necessary to harness already available and emerging software and hardware technologies. Computational capacity has increased by roughly three orders of magnitude in the past decade. The world's first exascale supercomputer entered production in 2022. Cloud resources now play a growing role in all aspects of HPC, data analysis, and storage. AI, machine learning, and data mining are increasingly used for improvement of numerical algorithms, model-data fusion, and analysis of big data produced by the models. These transformative advances in supercomputing present a unique and timely opportunity to tackle open questions involving cross-scale and cross-domain coupling (see Chapter 2), setting solar and space physics on the precipice of new discoveries. Moreover, it allows the United States to maintain leadership in space environment modeling, which has both scientific and national security implications.

To bring about this new era of discovery, the solar and space physics community needs a framework that allows models to efficiently utilize the largest supercomputers and other HPC systems and take advantage of cloud and AI resources, while enabling broad community participation in algorithmic and model development and use. Challenges in harnessing modern HPC technologies include porting highly complex models, often consisting of multiple interconnected components, to increasingly heterogeneous supercomputer architectures while in a way that achieves performance that allows capable simulations on a massive scale.

Development and maintenance of software for such models requires sustained curation of large and complex code bases and improving model fidelity, which demands a new level of error analysis, uncertainty quantification, and data assimilation. The implementation of sustained maintenance of large ensembles of curated uniform data streams, standardized file formats, and testbeds entails large intellectual, computational, communication, storage, and system administration resources. Open accessibility implies development and maintenance of software that will enable broad research community participation including contributions to open source code development, performing model runs, and carrying out analyses based on simulation data. All the above requires sustained infrastructure for training, hiring, and retaining a new type of interdisciplinary workforce with overlapping expertise ranging from HPC-specialized research software engineers to experienced applied mathematicians, domain scientists, and program managers. Such a sustained, professional workforce is paramount to meeting the nascent modeling challenges in solar and space physics but is not being achieved within the current hierarchy of the funding programs.

The solar and space physics community is ready to embrace the open science and open software paradigms. However, even the largest modeling programs currently cannot efficiently serve the broader community, because the programs do not have the resources to recruit the necessary workforce, nor do they possess the sustained infrastructure to retain it. Therefore, a new paradigm is necessary to implement an open science approach to solar and space physics modeling. This new paradigm should incentivize and develop the new modeling workforce in ways that allow appropriate prioritization of both scientific throughput and development of community models. The flagship-level community modeling program recommended below would be a prime example of NASA's commitment to open science.

Conclusion: A significant expansion of the funding hierarchy for theory and modeling is needed to meet the challenges of ever-increasing physical complexity of the models, rapid development of the high-performance computing landscape, and adherence to open science standards.

Recommendation 5-4: In addition to maintaining the current range of grant opportunities for theory and modeling, the National Aeronautics and Space Administration (NASA) should establish a flagship-level heliophysics community science modeling program capable of addressing heliophysics problems that have broad community interest and that require complex community models. This program should be funded at a level that enables training, hiring, and retaining interdisciplinary teams of highly specialized professionals. NASA should establish a sustained

infrastructure for these core teams to engage community participation in developing, using, and maintaining the models. To define and implement the program, NASA Heliophysics Division should gather community input and consider examples (e.g., the various Earth system models) from other NASA divisions, other federal agencies, and international organizations.

A critical part of space weather operations is the use of models, data assimilation, and AI methods. The use of these methods assembles available observations into a coherent framework that describes the past sequence of events and predicts future evolution. The NASA flagship community science modeling program described above focuses on the three science themes of Chapter 2 and not on real-time monitoring and predictions. Thus, the operational space weather organizations should join forces to support a parallel modeling effort where the increased scientific understanding from the flagship community model is transitioned to operational services, as described in Chapter 3, Recommendation 3-4.

5.2.3 Space-Based Assets in the Integrated HSL

The science and space weather guiding questions and focus areas introduced in Chapters 2 and 3 require an integrated HSL that has a wide array of space-based measurements. Measurements of the heliosystems include remote sensing and in situ techniques. Most often, remote sensing requires space-based observation platforms because of the need to have different vantage points, duration and cadence of the measurements, and measurements above the dense atmosphere of Earth. In addition, almost every science focus area in Chapter 2 requires in situ measurements of plasmas (including thermal plasma through energetic particles), neutrals, and magnetic and electric fields in regions from very close to the Sun and Earth to out into the local interstellar medium.

Figure 5-8 shows that the NASA space-based and selected NSF-funded elements of the integrated HSL include NASA and NSF CubeSats, sounding rockets, balloons, the existing HSO, the Explorers and Missions of Opportunity (MOs), space weather missions, and the STP and LWS Heliophysics mission lines. Cross-divisional collaboration within NASA brings in measurements of the interplanetary medium by planetary missions in their cruise phase between Earth and their planetary targets, as well as potential data from the outer heliosphere boundaries from the Planetary Science Division's New Horizons mission. Figure 5-8 also shows selected NSF facilities, including the recently commissioned Inouye Solar Telescope and the new ground-based facilities recommended by this decadal survey. In the next decade, combining ground-based and space-based assets is important for the comprehensive research strategy.

Acquiring these measurements requires data links from the space-based assets to the ground. These links become increasingly challenging as the number of space-based assets increases and the assets move farther from Earth into interplanetary and even interstellar space. In addition, new, increasingly sophisticated instruments produce large quantities of data while science investigations require measurements at high cadence and space weather operations require these measurements in (near) real time. Thus, continuous transfer of large data quantities over long distances becomes a significant bottleneck to achieving both the science and space weather goals. Elimination of these bottlenecks requires upgrades and expansion of data receiving and processing ground facilities; specific recommendations for these communications facilities are provided in Section 5.4.

NASA Suborbital Program

From its inception, NASA's suborbital Sounding Rocket and Scientific Balloons Programs have had a two-pronged focus on both technology development and science. These smaller- and shorter-timescale projects have provided significant achievements both independently focusing on targeted research questions and as complementary elements in support of larger missions. In addition, the program has advanced instrument concepts for future explorer and strategic missions and expertise in the solar and space physics community. For example, the Twin Rocket Investigation of Cusp Electrodynamics (TRICE-2) sounding rockets produced significant science results on the physics in Earth's magnetospheric cusps, while providing a significant technology development step for the Tandem Reconnection And Cusp Electrodynamics Reconnaissance Satellites (TRACERS) Small Explorer (SMEX) mission. Another highly prolific suborbital mission has been the Balloon Array for Radiation-belt Relativistic Electron Losses (BARREL) mission that flew multiple campaigns during the Van Allen Probes era (and beyond). BARREL

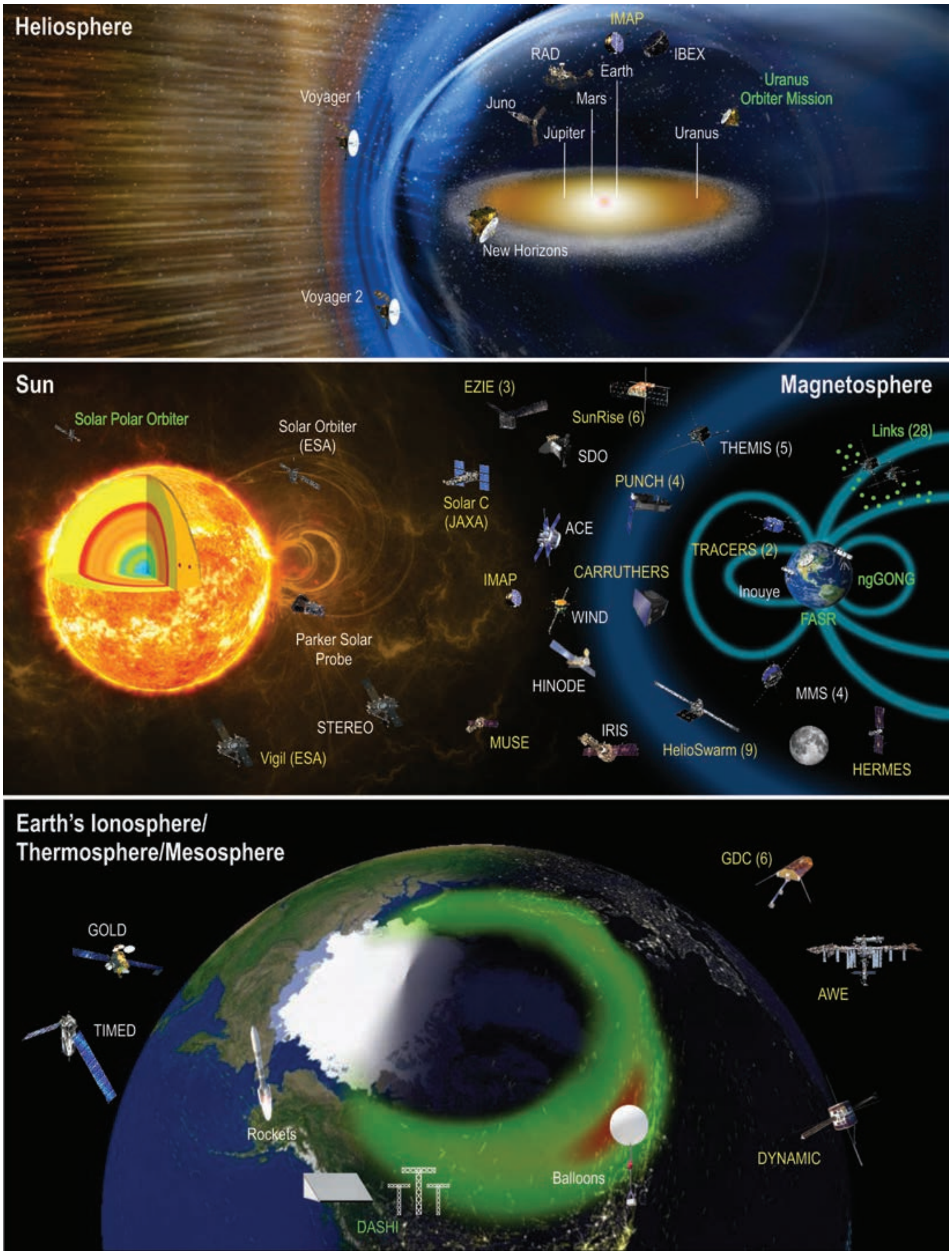

FIGURE 5-8 NASA space-based and select National Science Foundation (NSF)-funded elements of the integrated HelioSystems Laboratory segregated by region. Elements in white are currently operational. Elements in yellow will be launched in the next decade. Elements in green are recommended by this decadal survey.
NOTE: Acronyms provided in Appendix H.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; (*Top*) Background elements from NASA/Johns Hopkins APL/SwRI/Steve Gribben; (*Middle*) Sun background from NASA/Goddard; Magnetosphere background from SwRI; (*Bottom*) Earth background from NOAA.

provided unique scientific insight as well as providing context for and comparison to Van Allen Probes radiation belt observations.

The sounding rocket program provides primary access to the "ignorosphere" at 80–300 km in altitude, where satellite orbits rapidly decay, and balloons cannot reach. However, the fundamental plasma physics that can be studied in this hard-to-reach region is not to be underestimated: neutral winds and upper atmosphere composition, auroral emissions and related current structures, energy dissipation through Joule heating and wave-particle interactions all are fundamental aspects of the ITM system and its coupling to the magnetosphere above and atmosphere below.

The high-altitude balloon program has been instrumental in accessing the upper atmosphere and viewing space from a stable platform that can stay aloft for days to weeks (in contrast to sounding rockets whose flights last on the order of 10 minutes). Balloon programs have contributed valuable science to studies of the Sun, the auroras, and other emissions from particle precipitation and its impacts on the upper atmosphere.

While suborbital flights are often used as testbeds for new instrument and concept developments, they also provide training of students and early career researchers in the rigors of spaceflight missions, preparing them for future hardware responsibilities and leadership positions. Rocket and balloon missions are ideal training grounds for future PIs of Explorer missions, instrument suites, and other mission involvement. The skillsets developed include exposure to the NASA mission architecture, team management, complex budget and schedule preparation, and a multitude of leadership credentials. The support and expansion of these programs is vital to producing a future set of instrument-providers and leaders for NASA PI-led missions (see also Section 5.3).

NASA and NSF CubeSats

The proliferation and capabilities of CubeSats have grown significantly over the past decade since NSF took the lead by implementing a modest but highly successful CubeSat program in 2008. One of NSF's first missions, CSSWE (Colorado Student Space Weather Experiment) was launched in 2012 and contributed to at least 24 peer-reviewed publications, including in the journal *Nature* (Baker et al. 2014; Li et al. 2017). In a review of early CubeSat missions, Spence et al. (2022) quantitatively demonstrated that they had weighted publication impact factors comparable to those of larger missions. CubeSats (e.g., CSSWE and Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics [FIREBIRD]) have also been used in support of major missions such as NASA's Van Allen Probes.

NASA provided technical support for NSF's program early on, and the agencies have jointly supported projects. The highly successful Electron Losses and Fields Investigation (ELFIN) mission made groundbreaking discoveries about radiation belt electron precipitation and plasma wave-particle interactions. To date, more than 35 peer-reviewed publications in high-impact journals are based on ELFIN observations. Since the 2015 launch of the first NASA Heliophysics Division science CubeSat, the Miniature X-ray Solar Spectrometer (MinXSS),[9] NASA's CubeSat program has expanded significantly. As of early 2024, 13 CubeSat missions had launched, and 14 were in development.[10]

Although typically funded through the research and analysis (R&A) program, suborbital and CubeSat projects are included in the HSL because of their scientific and data contributions. With the intention to offer low-cost access to space, the CubeSat program provides important program balance at NASA. However, a program that was envisioned originally as inexpensive (~$1 million per mission) has grown in complexity and cost (current mission costs range between $4 million and $8 million) and has been hampered by internal and external problems; even with the explosion of launches by the commercial sector, launch opportunities for CubeSats suffer from lengthy delays and cost growth. New launch companies available through the Venture Class Launch Service (VCLS) demonstrations have been plagued by delays and launch failures. The COVID-19 pandemic had a significant impact both on teams and on the supply chain. Although these issues are mostly resolved, CubeSat projects, which may have all the complexities of a larger mission, have no reserves and therefore less resiliency to deal with problems.

[9] MinXSS made new observations of the solar X-ray spectrum, was the first CubeSat mission to demonstrate pointing control better than 10 arcsec and led to more than 30 publications. It was followed by MinXSS-2, which was launched in 2018.

[10] This number does not include CubeSats that are part of larger missions—for example, Explorers—which are becoming more common. See NASA (2024c).

As the costs have increased, the engagement of smaller institutions and early career PIs has become increasingly challenging, because they may not have sufficient resources in the proposal phase to compete against institutions that have large internal teams and funding. Furthermore, there is growing concern over the right level of management oversight, which contributes to the increased total program costs.

The community has also voiced a need for better support for project teams in addressing issues such as radio licensing and ground station access, as well as better opportunities for community input to NASA and sharing of lessons learned. Maximizing the return on investment in the CubeSat program calls for assessment of project costs, program structure, as well as identification of potential solutions to the challenges described above. After nearly a decade over which the program has grown, a review to ensure its continued success would be beneficial.

The NSF CubeSat program, despite its early successes, appears to have stagnated. The midterm assessment of the 2013 decadal survey pointed out that the CubeSat solicitation was not offered in 2016 or 2017 when the program was reinvented as the Foundation-wide CubeSat Ideas Lab program. In 2022, five NSF-supported CubeSat missions were expected to launch in 2023–2024 timeframe (Sharma 2022). However, the agency has not solicited new proposals since 2019. The Physics Division has established a new cross-NSF program in partnership with the GEO and ENG directorates—Ecosystem for Leading Innovation in Plasma Science and Engineering (ECLIPSE), which supports sensor development for CubeSats (NSF n.d.). The 2017 National Academies of Sciences, Engineering, and Medicine's report *Assessment of the National Science Foundation's 2015 Geospace Portfolio Review* recommended that "the NSF Geospace Section carefully consider the impact associated with decreasing funding for the CubeSat program before additional resources through intra-divisional partnerships can be obtained" (NASEM 2017, p. 35).

Conclusion: The CubeSat programs at NASA and NSF are important elements of the HSL, contributing data and scientific results. These programs continue to be valuable and need to continue meeting the original goals of science, training, and participation.

Recommendation 5-5: To ensure continued success, the National Aeronautics and Space Administration and the National Science Foundation should conduct comprehensive, community-based reviews of their CubeSat programs.

Recommendation 5-5 is written generally so that NASA and NSF determine their own means to go about the review of CubeSat programs. However, important aspects to consider include, but are not limited to, the following:

- Balance between technology demonstration, education, and science investigations and the appropriate risk postures for each;
- Methods for sharing lessons learned and enhancing support for potential or inexperienced PIs. One possibility would be to expand activities where experienced NASA scientists and engineers work directly with the project team;
- Facilitation of cross-government coordination and identification of areas where funding agencies could provide additional guidance or support—for example, when applying for a radio license or other regulatory requirements;
- Appropriate levels of management and oversight;
- More formalized means for community input to the agencies. For example, NASA's Sounding Rocket Working Group is a possible model for this input;
- Evaluation of current access to space—for example, an assessment of time from selection to launch, launch success rates, availability of CubeSat Launch Initiative–supported launches and other potential opportunities for funding launches; and
- Appropriate levels of funding needed to maintain a robust program.

The increased costs of NASA MOs (see the next section) have created a gap in the funding between the current CubeSat funding level (~$4 million to $8 million) and the lower end of the MOs ($35 million). Missions in this gap could include larger balloon or rocket missions or multiple CubeSats—for example, for science requiring multipoint measurements or larger suborbital launches. Similar gaps in the Astrophysics and Earth Science Divisions were recently filled with the new Pioneers Program and with Earth Venture instruments, respectively. The implications of this gap in Heliophysics should be considered, because such gaps affect program balance within NASA.

Recommendation 5-6: The National Aeronautics and Space Administration should create opportunities for principal investigator–led projects in the size range $10 million to $35 million (not including launch costs) that could accept higher risk than the Missions of Opportunity and be realized with minimal requirements for mission assurance and agency oversight.

This program could be implemented quickly and in a cost-effective manner if the Heliophysics Division partnered with or otherwise leveraged the approach of the Astrophysics Pioneers Program.

NOAA Space Weather Observations

The current NOAA missions monitor the Sun and the space environment, providing the data needed to make operative space weather forecasts and predictions. Future missions are designed to provide continuous monitoring of the Sun and the space environment well into the next decade (see Figure 5-9). These future missions include the Space Weather Follow-On Lagrange 1 (SWFO-L1) and Space Weather Next programs. There is substantial

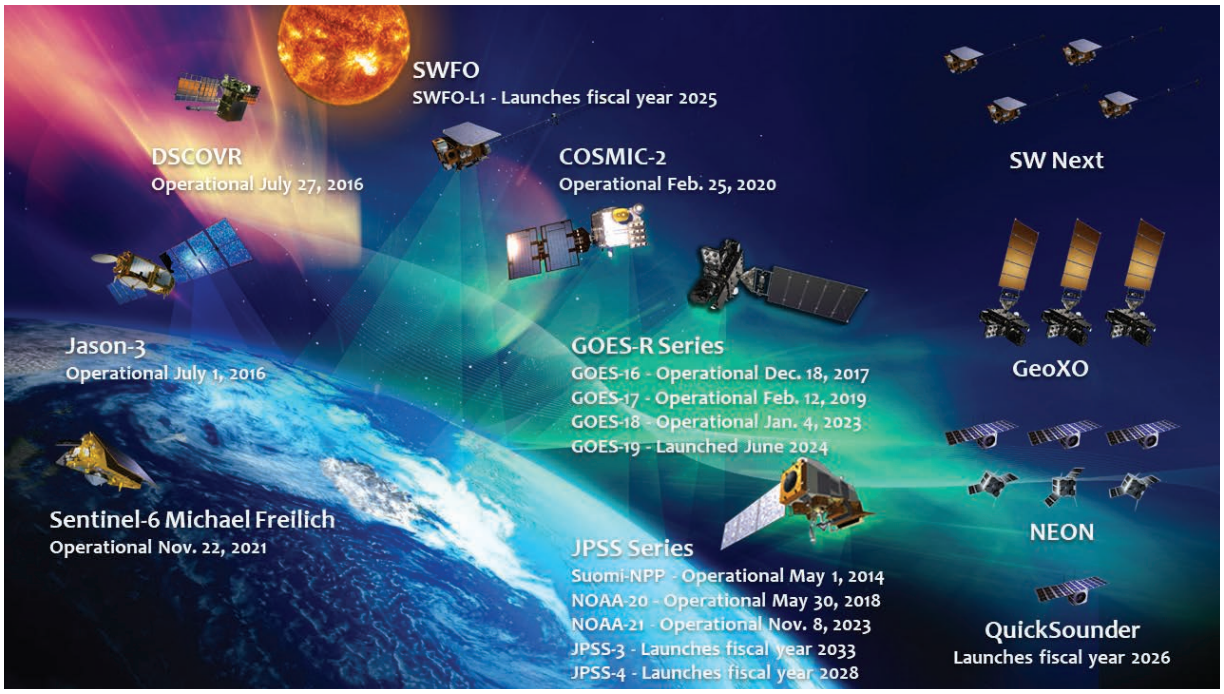

FIGURE 5-9 NOAA satellite missions. This extensive fleet of operational, environmental, and other satellites includes instruments that provide continuous monitoring of the space environment and space weather, informing space weather science and feeding space weather models. NOAA's space weather fleet consists of DSCOVR at L1, COSMIC-2 in LEO, and the GOES-R series in GEO. New to the fleet is the compact coronagraph, introduced on GOES-19 and planned for SWFO-L1 and the first project in the Space Weather Next Program, Space weather Observations at L1 (SOL).
NOTES: Acronyms provided in Appendix H. The image and caption were modified after release of the report to clarify which NOAA satellite missions are for space weather.
SOURCE: NOAA.

international involvement in these missions. The SWFO-L1 mission, scheduled for launch in 2025, requires an international ground network for 24/7 mission data acquisition. A number of agreements are in place (Japan's National Institute of Information Technology and Communications and Korea Radio Research Agency) or are being negotiated (South Africa and Brazil) to continue the Real Time Solar Wind network (RTSWnet) and supplement the SWFO antenna network. Discussions are under way with the Indian Space Research Organization to explore opportunities for collaboration—for example, data exchanges between SWFO-L1 and Aditya L-1. Space Weather Next program has multiple project components designed to extend space weather observations to a variety of critical vantage points: from L1 and L5 orbits, geostationary orbit, low Earth orbit (LEO), and ground support networks. NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) will provide a compact coronagraph to be hosted on ESA's Vigil mission (2031 launch) and is exploring other instrument hosting opportunities with other international hosts, including the Canadian Space Agency, the Taiwan Space Agency, and the Korea AeroSpace Administration.

In addition to their primary monitoring task, these missions produce a wealth of data that support research space weather science and guide development of models used in forecasting and predicting space weather. It is important that NOAA develop systems to make those data readily available to the research community in a format that is compatible with other data sources.

While the decadal survey committee acknowledges and supports the NOAA satellite missions, it was not tasked with assessing the current and future monitoring missions or providing recommendations on their operational aspects. However, there are findings and recommendations of this decadal survey that focus on space weather research, the research to operations transfer, and the operations to research feedback (research to operations to research [R2O2R]). Space weather research and R2O2R pervades all solar and space physics, to the extent that it is included as a second part of the mission statement of this decadal survey—*to serve humanity*.

NASA Space Weather Program

The NASA Space Weather Program provides explicit transition of scientific knowledge to operational applications (see Figure 5-11). The Space Weather Program will provide a space weather science instrument on the ESA Vigil mission. Vigil (previously known as Lagrange) is an ESA space weather mission to observe the Sun from the Sun–Earth Lagrange point L5, away from the Sun–Earth line. This vantage point allows the propagation of coronal mass ejections emitted by the Sun toward Earth to be observed, as well as observations of the solar disk before it rotates into view from Earth. The Vigil mission will image the solar disk and corona as well as the inner heliosphere and measure the interplanetary medium at its location at 1 AU. The remote sensing instrument provided by the NASA Space Weather Program fills the gap between the Vigil photospheric magnetograph and the coronagraph provided by NOAA. The inclusion of a space weather monitoring instrument on a partner's mission is a blueprint for future monitoring instruments onboard other NASA and international space missions.

As part of the Artemis program, the Lunar Gateway will be a Moon-orbiting outpost for astronauts heading to and from the lunar surface. Gateway will carry the Space Weather Program Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES), which consists of four instruments monitoring space weather conditions in lunar orbit. Similar to the space weather monitoring instrument on Vigil, HERMES has basic science goals and also provides observations that will be useful for space weather monitoring.[11] HERMES is a blueprint for deployment of future monitoring instruments, for projects under the auspices of the Moon to Mars strategy.

Given the increased need for space weather services in the coming decade, the NASA Space Weather Program needs to grow with fresh funding that does not come at the expense of the Heliophysics Division science. Specifically, funding for instruments that are vital for the safety of the lunar infrastructure and humans needs to be covered from sources outside the Heliophysics budget. In addition, if the Space Weather Program funding were sufficient, the program could fund model improvement efforts and analysis to demonstrate its operational effectiveness. The resulting techniques that showed sufficient improvement in forecasting and specification skill would then be candidates for transition to operations. As with the transition of instruments to operational status,

[11] This paragraph was modified after release of the report to accurately reflect the purpose of HERMES.

the transition of models to operational status requires close coordination with NOAA. This NASA and NOAA modeling effort is part of the larger R2O2R framework described in Section 3.3.1.

The Space Weather Program recommended for the next decade includes funding for a stand-alone mission up to the size of a SMEX as well as MOs. The program is designed to provide NASA with the means and flexibility to conduct stand-alone missions as needed. These missions would complement the Space Weather Program initiatives by providing demonstration instruments for missions carried out by other agencies and international partners. In keeping with the overall charter of the Space Weather Program, target objectives of these stand-alone missions need to be based on those observations or techniques that have been identified as showing promise for implementation as operational components of NOAA's space-based fleet. NASA and NOAA need to work together to develop metrics and transition plans to transfer research results to NOAA operations, as recommended in Chapter 3 (see Recommendation 3-5).

The Panel on Space Weather Science and Applications (see Appendix E) reviewed the space weather value of all the missions that went through the evaluation (i.e., technical, risk, and cost evaluation [TRACE]) process (see Appendix G). The panel also suggested potential space weather enhancements for NASA missions. (See Chapter 3, Recommendation 3-6.) These add-ons range from enhanced data acquisition, modification of proposed instrumentation, to addition of space weather–related demonstration or even operational instrumentation. The panel review concluded that all new Heliophysics Division missions have the potential for space weather enhancements. Specifically, LEO satellites are ideal platforms to host GNSS receivers with upgraded firmware that enables total electron content (TEC) measurements, while medium Earth orbit (MEO) and highly elliptical orbit (HEO) satellites could host charge-discharge sensors. Orbits beyond Earth orbit are ideal for hosting sensors for measuring solar energetic particles. Space weather enhancements are best accommodated early in the mission development. Space weather is further discussed below.

Heliophysics System Observatory

The HSO comprises a wide range of space-based missions that are in its extended mission operations phase. Figure 5-8 contains the current HSO as part of the HSL but does not show the important contributions to the HSO from NOAA assets. Over the past decade, this observatory has grown in size and range of observations as many Explorer and larger-class missions have reached the end of their prime mission and have successfully completed senior reviews that emphasize new systems science objectives within the HSO. In fact, of the missions in Figure 5-8 that are currently in operation, only two, Parker Solar Probe (PSP) and Solar Orbiter, are in their prime mission phase. In addition, NASA has created and, in the 2023 senior review, greatly expanded a new infrastructure category for the HSO. The Solar and Heliospheric Observatory (SOHO), Advanced Composition Explorer (ACE), and Wind were a part of the original infrastructure category. Following the 2023 senior review, new infrastructure missions—Global-scale Observations of the Limb and Disk (GOLD), Hinode, Solar Dynamics Observatory (SDO), Solar Terrestrial Relations Observatory (STEREO), Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED), and Voyager—receive funding solely to continue operations for the next 3 years. In the future, these and the other infrastructure missions are invited to a programmatic review that is on a similar cadence as the senior review. The Interface Region Imaging Spectrograph (IRIS), THEMIS, Interstellar Boundary Explorer (IBEX), and Magnetospheric Multiscale Mission (MMS), which currently make up the rest of the HSO missions in extended operations, continue both operations and science. Additionally, NASA has been developing capabilities of the Heliophysics Digital Resource Library's with an intent to integrate it into the management of the HSO mission data sets.

The combined fleet of infrastructure and science missions is considered as a single observatory, in effect a large-scale heterogeneous constellation. The value of the HSO in the previous decade was dramatically illustrated by numerous solar flare observations. Simultaneous observation by multiple HSO assets enabled major breakthroughs in the understanding of explosive energetic releases. For example, the flare on September 10, 2017, was simultaneously observed over the entire electromagnetic spectrum by NASA missions (SDO, IRIS, Reuven Ramaty High Energy Solar Spectroscopic Imager [RHESSI], Fermi), international spacecraft (SOHO, Hinode, Project for Onboard Autonomy 2 [PROBA2]), NOAA assets (Geostationary Operational Environmental Satellites

[GOES]/Solar Ultraviolet Imager [SUVI]), and ground-based observatories (EOVSA, Coronal Multi-Channel Polarimeter [CoMP], Low-Frequency Array [LOFAR]), and by ground-based neutron monitors. The multitude of observations measured the magnetic field strength along the current sheet, mapped out locations in the sheet where electrons were energized, and located the position within the current sheet where magnetic reconnection occurred and energy was released.

In the magnetosphere, fortuitous conjunctions of HSO spacecraft and NOAA assets offered glimpses of the highly complex magnetospheric dynamics, its response to various driving conditions, and highlighted the potential for future multispacecraft observations at various scales and in different regions. For example, a study involving GOES 13 and three THEMIS satellites found the first evidence that magnetic reconnection very close to Earth (near geosynchronous orbit, at 6.6–10 Earth radii [R_E]) could power intense geomagnetic storms. Another multispacecraft conjunction study using MMS, THEMIS, Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS), Van Allen Probes, and Cluster observations led to new understanding of the extreme thinning and stability properties of the magnetotail current sheet during active geomagnetic conditions. Simultaneous observations by Van Allen Probes, THEMIS, MMS, and GOES were used to probe the extreme variability of Earth's outer radiation belt electrons, addressing the role of electron acceleration in the magnetotail as a possible source of outer belt electrons. These studies have made it clear that understanding the entire inter-connected system that makes up the magnetosphere, ionosphere, thermosphere, and mesosphere requires coordinated multiregion and multiscale observations.

For the systems science–focused themes of this decadal survey, constellation missions, new vantage points, and the HSO become critical elements of the research strategy. The distributed HSO has flexibility and capabilities that evolve with each new mission launched. Its current composition includes a significant number of diverse solar, heliospheric, and magnetospheric missions. However, with the loss of the Ionospheric Connection Explorer (ICON) spacecraft (after its highly successful prime and extended missions), there is a dearth of upper atmosphere (ITM) missions (see Figure 5-8). This shortcoming is remedied only when GDC and DYNAMIC are launched and included in the HSO near the end of the next decade.

NASA is actively engaged with the international community through HSO missions such as Hinode, IRIS, PSP, Solar Orbiter, Wind, SOHO, STEREO, MMS, and THEMIS. In the next decade, the importance of international missions in the HSO and the integrated HSL will continue to grow. Inner-heliospheric research takes on a much more international character with the inclusion of some important international missions, such as the BepiColombo dual-spacecraft mission to Mercury, and later in the survey interval, the Vigil and Solar-C missions observing the Sun and the solar wind. This international character could be strengthened even more if other space agencies, like the Indian Space Research Organization (ISRO) and the newly established Korean Aerospace Administration (KASA), are included in the HSL. The combination of these remote and in situ inner heliospheric measurements forms an unprecedented inner heliosphere observational capability in the next decade. Figure 5-10 illustrates the opportunities to measure the inner heliosphere either over a range of radial distances along a Parker spiral establishing a magnetic connection between the measurements (top panel) or a wide range of longitudes covering the global solar activity (bottom panel). The coordinated use of this fleet of spacecraft is a pathfinder for future science of the Sun and inner heliosphere—in particular, propagation of disturbances from the Sun to and beyond 1 AU.

Multiagency Support for Space Weather

While the NASA Heliophysics Division and NSF programs are focused on fundamental science and understanding of the local cosmos, space weather research is inseparably intertwined with the fundamental research.

Table 5-5 summarizes assets in the NSF, NOAA, and NASA programs of record (both operative and upcoming) and their space weather potential. The plans for ngGONG (see Section 5.2.2) include a space weather component from the planning of the infrastructure, while the other assets are scientific instruments that provide valuable space weather monitoring capabilities if the data are received and distributed to the users in a timely manner.

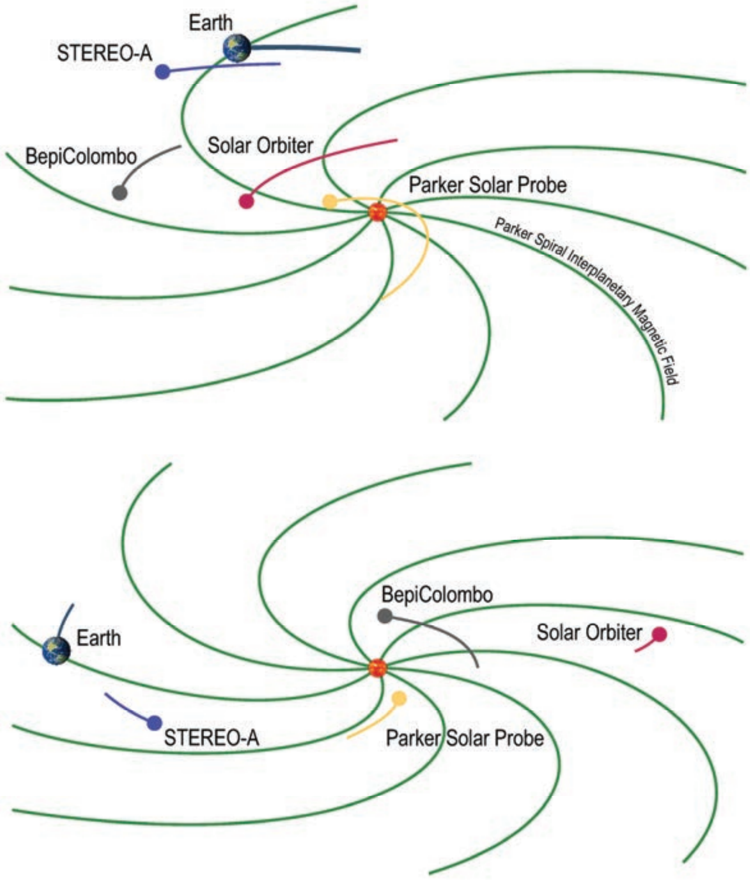

FIGURE 5-10 International cooperation is a key element of the Heliophysics System Observatory. These two panels show satellite conjunctions in the inner heliosphere where the NASA and international assets are (*Top*) aligned along a single Parker spiral interplanetary magnetic field and (*Bottom*) where they are spread over a wide range of longitudes and radial distances. SOURCE: Composed by AJ Galaviz III, Southwest Research Institute.

Figure 5-11 shows the relationship between the two NASA mission programs (STP and LWS), the NASA Space Weather Program, and their direct linkage to NOAA operational missions. The LWS program focuses on basic science that targets questions that have relevance for space weather prediction capabilities. However, the boundaries between the STP and LWS programs are somewhat diffuse, as improvement or development of almost any space weather capability still relies on new fundamental research results. Moreover, many of the past STP missions have contributed greatly to understanding space weather phenomena from the Sun (STEREO) to the magnetospheric (MMS) and ionospheric (TIMED) processes.

For decades, the NASA Heliophysics program has provided critical solar (SOHO, SDO, STEREO) and solar wind observations (ACE, WIND) to the NOAA SWPC for its operational space weather products. The research strategy for the next decade includes the space weather IMAP Active Link for Real-Time (I-AliRT) system (Spann et al. 2023) on the IMAP mission and opens additional, new opportunities for using magnetospheric and ionospheric observations for operational purposes. Moreover, CubeSats, sounding rockets, balloons, and Explorer missions bring new elements to understanding, predicting, and monitoring space weather (see Figure 5-8).

In the next decade, ITM space weather research is enhanced significantly with the launch of GDC and DYNAMIC. These two upper-atmosphere missions form a coordinated constellation, where GDC observes

TABLE 5-5 Current and Future Missions and Projects and Their Capabilities for Space Weather

		Instrument/Mission		
Agency	Domain	Current	Future	Space Weather Capability
NSF	Solar	GONG	ngGONG	Solar magnetic field
			FASR	Solar spectroscopy, coronal field, energetic phenomena, and space weather drivers
			COSMO	Solar magnetic field
	Magnetosphere	AMPERE	AMPERE-Next	Field-aligned currents
	Magnetosphere–ionosphere–thermosphere		DASHI	Ionospheric parameters and ground magnetic variations
	Ionosphere–thermosphere		GNSS Network	Ionospheric scintillations and total electron content (TEC)
			LiDAR Facility	Neutral atmosphere parameters
			Meteor Radar Network	Neutral winds
		Incoherent scatter radars (PFISR/RISR)	Midlatitude, refurbished PFISR/RISR/Subauroral	Ionospheric electron density
		SuperDARN		Ionospheric convection
NOAA	LEO	COSMIC-2		TEC, ionospheric electron density, ionospheric scintillation, and ion density
		Commercial Data Program		Ionospheric electron density and TEC
		POES/METOP		Space environment monitor
	GEO	GOES-R series	Space Weather Next GEO missions	B-field, plasma, energetic particles, solar X-rays, and EUV
	L1	DSCOVR	SWFO-L1, Space Weather Next SOL (formerly Space Weather Next L1 Series)	Solar wind and interplanetary magnetic field (IMF); coronagraph imagery and suprathermal ions (future missions only)
	L5		Vigil	Coronagraph imagery
			HERMES	Energetic particles and magnetic fields
NASA Program of Record	Solar and solar wind	ACE		Solar wind and IMF
		Wind		Solar wind and IMF
		IRIS		Solar imaging and spectroscopy
		SDO		Solar imaging, magnetic field
		STEREO		Solar imaging
		SOHO		Solar imaging
		PSP		Solar wind and IMF

TABLE 5-5 Continued

Agency	Domain	Instrument/Mission Current	Instrument/Mission Future	Space Weather Capability
		Solar Orbiter		Solar wind and IMF, solar imaging, and spectroscopy
			EUVST	Solar imaging and spectroscopy
			HelioSwarm	Solar wind turbulence
			MUSE	Solar imaging and spectroscopy
			PUNCH	Solar imaging
			SunRISE	Solar radio emissions
			IMAP	I-ALiRT monitoring, solar wind, and IMF
	Magnetosphere	THEMIS		Magnetospheric plasmas and fields
		Artemis		Plasmas and fields in lunar orbit
		MMS		Magnetospheric plasmas and fields
			EZIE	Auroral electrojet
			TRACERS	Magnetopause reconnection
	Ionosphere		GDC	Auroral precipitation, ionospheric electron density, thermospheric winds, and waves
			DYNAMIC	Thermospheric winds and waves, auroral imaging, and ion composition
			Carruthers	Exospheric imaging
	Ionosphere-Thermosphere-Mesosphere	AWE		Atmospheric waves
	Planetary		ESCAPADE	Energetic particles at Mars

NOTES: Acronyms provided in Appendix H. This table was modified after release of the report to accurately reflect NOAA's current and future missions and projects, as of the time the report was written.

Earth's high-latitude energy and momentum input resulting from coupling with solar wind and magnetosphere and DYNAMIC measures momentum and energy forcing resulting from coupling with the lower atmosphere through waves. In addition, GDC and DYNAMIC will trace the global energy and momentum transport through the ITM system and record the impacts on the global dynamical state of the system. These NASA observations will be made available in near real time to NOAA through optimized transmission content and latency for NOAA's space weather notification system.

The near-real-time observations will contribute to space weather by (1) providing situation awareness data and space traffic management services to commercial space operators especially at LEO; (2) notifying operators providing communications, navigations, and surveillance services of the radio propagation conditions; (3) providing geomagnetic activity information to power grid and other system operators; and (4) monitoring the LEO radiation environment impacting spacecraft systems and human health.

As mentioned above, the Panel on Space Weather Science and Applications suggested space weather enhancements for NASA missions. These enhancements are significant because they provide a direct link between the NASA Heliophysics Division and the research to operations efforts of NASA and NOAA. Such enhancements

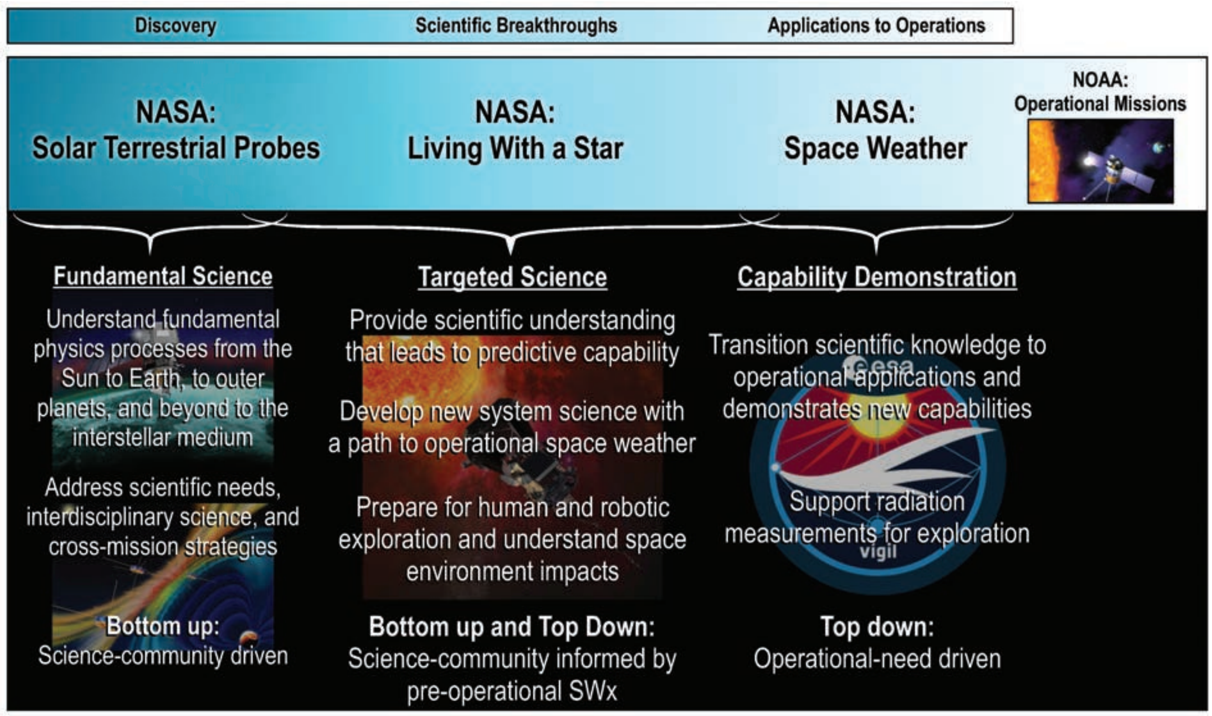

FIGURE 5-11 NASA mission programs and Space Weather Program and their relationship to space weather and NOAA operational missions. The boundaries between different programs are somewhat diffuse, as the same assets are used to address multiple needs from fundamental research to capability demonstration of operational space weather observations.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Left and middle background and upper right inset images from NASA; Right background image from ESA.

could also be included on NOAA operational missions as well as missions led by other federal agencies, given sufficient lead time in the mission development. Each additional datapoint in the sparse network is an important addition for space weather predictions; therefore, it is imperative to take advantage of all opportunities to increase the observational coverage. Each time an agency plans a new spacecraft or a ground-based facility, it would be advantageous to assess whether a space weather instrument, data stream, or other space weather component could add value at a reasonable cost. Instrument add-ons are best accommodated early in the mission development, which implies that it would be desirable to have an early space weather assessment as a standard practice by the agencies.

The NASA Explorer Program

The Explorer program is as old as NASA itself. The first U.S. satellite, Explorer 1, discovered Earth's magnetosphere and radiation belts. Since then, the increased cadence and diversification of the mission classes has resulted in a program that responds rapidly and cost-effectively to science opportunities that evolve over the decadal survey intervals. The program has been an outstanding success, with missions that uniformly achieve their focused science objectives and provide major, new science results during their extended missions. The existing Explorers are critically important and cost-effective components to the HSO and hence the HSL. Truly, the Explorer program lives up to its name, providing exploratory science that paves the way for strategic missions. An outstanding, recent example is the IBEX SMEX, whose discoveries informed many of the science objectives for the strategic STP IMAP mission.

A significant success in the previous decade, following from recommendations by the 2013 decadal survey, was the increase in the cadence of Explorer solicitations. The increase to a cadence of 2–3 years, the inclusion of MOs in every solicitation, and alternating MIDEX and SMEX solicitations have resulted in a vibrant, cost-effective program that serves a significant portion of the solar and space physics community. The increased cadence has in no way diminished the quality and quantity of selectable Explorer proposals.

However, the success of the Explorer program, combined with other changes in the operational environment, has come with some unintended consequences. Improved spacecraft reliability and long lifetimes have increased the costs of extended mission operations, putting additional pressure on the Explorer budget. Selection delays, supply chain and workforce issues during the COVID-19 pandemic, the pace of mission selection (two SMEX missions in 2019 and two MIDEX missions in 2022), and Heliophysics budget pressures have resulted in an Explorer program that will grow to encompass >40 percent of the total current Heliophysics Division budget by 2026. The trend of increased management oversight (see NASEM 2020) is another cost-driver. In addition, any delays in the start of the mission development that follow from more than one Explorer selection have a disproportionate impact on smaller institutions that do not have institutional resources to keep a team together when project funding is reduced or cut because of a delay. Last, implementing the nine Explorer missions currently in development requires more than one launch per year over the next decade to resolve the backlog.

Conclusion: The 2013 decadal survey recommendation for Explorers cadence (2–3 years) assumed a single selection per opportunity. Selection of multiple missions, combined with other budget pressures, has put pressure on other important programs.

Figure 5-12 shows recent PI-managed cost caps for different classes of Explorers and MOs. At the lower end of the cost scale for the Explorer program, the MOs offer an excellent opportunity for very targeted science and allow a wider range of participation in mission development. Recent MO solicitations were concurrent with other

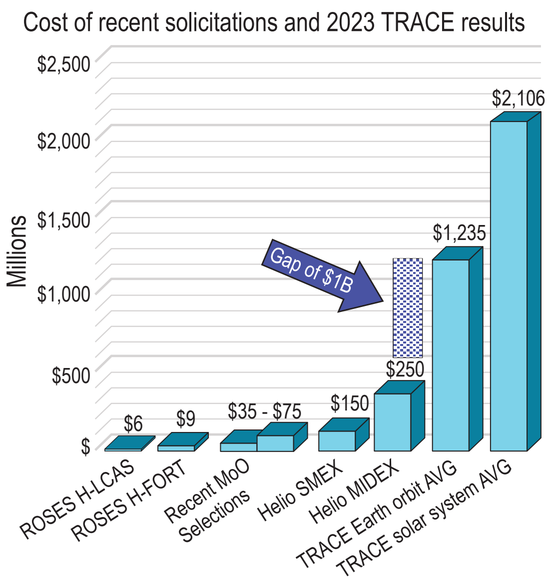

FIGURE 5-12 There is a significant mission cost gap between the Medium-Class Explorer and Living With a Star/Solar Terrestrial Probes missions, shown in the figure as TRACE Earth orbit average and TRACE solar system average mission costs. The introduction of a "Heliophysics Large Explorer" mission class would fill this cost gap and improve the mission cost balance within the Heliophysics Division.
NOTE: Acronyms provided in Appendix H.
SOURCE: Composed by AJ Galaviz III, Southwest Research Institute.

Explorer solicitations, even though the announcements of opportunity (AOs) are not the same (Stand Alone MO Notice Program Element Appendix versus standard AO), and the evaluation panels are different. Concurrent solicitations potentially disadvantage institutions that lack the resources to produce multiple proposals simultaneously, forcing proposers from these institutions to choose between proposing a MO and a full mission. The concurrent solicitations can have the effect of reducing the quantity and competitiveness of the MO proposals. This could have contributed to no MO being selected in the recent SMEX 2022 cycle.

At the upper end of the cost scale for the current Explorer program, the MIDEX missions offer an excellent opportunity to perform important science on a budget that falls between the SMEX budget and the strategic LWS and STP missions budgets. However, the current structure, implementation, and cost caps of the Explorer program are not conducive to launching the constellations of spacecraft needed for reaching the science goals of the next decade. The current Explorers cost cap and offered launch options limit constellations to ~10 CubeSats and a single launch. An increase in the MIDEX cost cap from $250 million to $300 million, as assumed for the next decade (see Chapter 6), does not substantially reduce these limitations. Furthermore, the current definitions and implementation of risk class and reliability focus on single flight systems or small constellations, which makes it difficult for constellation missions to compete against other missions in the current Explorer program. New approaches are needed to facilitate efficient operations and maintenance of these large constellations. Increased use of autonomy may be necessary to manage large constellations, in addition to new approaches to communications, including increased use of commercial providers or inter-satellite crosslinks. While the current cost caps limit the number of spacecraft in a constellation, there are other viable Explorer missions (small constellations of larger spacecraft and single spacecraft) that could fit within the cap.

Conclusion: Multipoint science observations and system science are the next frontier in heliophysics. Implementing large satellite constellations (≥24 satellites), as submitted in many community input papers to this decadal survey, is not feasible in the current Heliophysics Division–competed (PI-led) mission portfolios.

Conclusion: There is currently a significant gap in funding between MIDEX and the recommended strategic LWS and STP missions. This gap needs to be filled to maintain program cost balance across the Heliophysics Division.

These conclusions drive the following recommendations for necessary revisions to the Explorer program. These revisions are designed to enhance the effectiveness of an already extremely successful program and enhance accommodation of constellation missions. They clarify the recommended Explorer cadence, the association between Explorers and MOs, and add a new class to the Explorer program to fill an increased mission cost gap between the MIDEX missions and the strategic LWS and STP missions. Specifically, the addition of a new class of Explorers arises from the critical need for moderate-scale constellation missions.

Recommendation 5-7: The National Aeronautics and Space Administration should maintain a robust and vibrant Explorers program by

- **Adding a Heliophysics Large Explorer (HeLEX)-class mission to the Explorer line. The HeLEX-class mission should have a principal investigator–managed mission cost roughly twice that of the Medium-Class Explorer (MIDEX) and could be supported at least once per decade;**
- **Maintaining a balance in Explorer mission sizes by alternating opportunities; in the period of this decadal, the next Explorer opportunity should be MIDEX, followed by a Small Explorer (SMEX), then HeLEX and then SMEX;**
- **Striving to maintain a 2–3 year cadence for Explorers and a 2–3 year cadence for Missions of Opportunity (MOs);**
- **Carefully considering the balance of all mission sizes across the Heliophysics Division before selecting more than one Explorer mission after Phase A and ensure that the 2–3 year cadence can be maintained;**
- **Separating the announcement of opportunity and proposal cycles for MOs from those of the full missions (SMEX, MIDEX).**

This recommendation is also designed to improve the balance between different mission costs within the Heliophysics Division budget so that larger missions are competed less often than smaller missions. Also, the recommendation is designed to create a wider range of mission classes to provide opportunities for all types of solar and space physics institutions. One way to leverage these improvements and increase participation in the Explorer program is to select more mission concepts for funding for Phase A studies. For example, an extended Phase A study brought the SunRISE MO to successful completion with a launch date in 2024. Another way to leverage these improvements is to incentivize inclusive partnerships between large and small institutions or between NASA centers and small institutions. While these may be some obvious first steps for improvement, additional changes to this highly successful Explorer program beyond Recommendation 5-7 require careful analysis and development.

The recommendation for a HeLEX mission grew out of the increased gap between the MIDEX costs and the strategic programs (LWS and STP). The average costs of the strategic programs in Figure 5-12 are discussed in Chapter 6. The most pressing need from the community input papers and identified by the decadal survey panels is for larger and/or more heterogeneous constellations than currently possible under the current Explorer program cost cap. The New Frontiers missions in the Planetary Science Division and Astrophysics Probe Explorer in the Astrophysics Division have specific scientific focus areas. Similarly, the HeLEX solicitation could focus on system science objectives that might require multisatellite constellations. Appendix G, which contains the TRACE results, lists several multisatellite constellations that could be tailored to fit within the notional HeLEX cost cap.

Developing an AO for a HeLEX constellation solicitation through the Explorer program would offer to NASA a testbed for larger constellation missions. Such an AO would put the Heliophysics Division in a leadership position for setting policies on constellation missions and open possibilities for negotiations with the Launch Services Program on launch options that provide multiple targets (e.g., multiple orbital planes). In the longer term, an ongoing program would encourage development of capabilities (infrastructure and processes) to support procurement of multiple instruments and satellite systems by leveraging commercial capabilities. Per the TRACE analysis of missions in this decadal survey (see Appendix G), this procurement is one of the cost and schedule drivers for large constellations.

For programmatic balance, it would be advantageous to alternate the HeLEX solicitation with the MIDEX solicitation. For example, a possible nominal sequence could be to have the first HeLEX solicitation in 2031 (replacing the MIDEX solicitation in that year). The 2–3 year cadence of MIDEX (nominally in 2025)–SMEX–HeLEX–SMEX–MIDEX, and so on, with MO opportunities on the same cadence, would maintain a strong, balanced, and stable Explorer program that would continue to produce world-class science.

LWS and STP Missions

Major discovery-level science and significant progress on the guiding questions and focus areas discussed in Chapter 2 requires major missions that have resources and complexity beyond the Explorer-class missions described above. In the next decade's research strategy, these missions are implemented within the Heliophysics Division's two major programs: STP and LWS. The distinguishing characteristics of these two programs are summarized in Figure 5-11.

STP missions are driven by the need of the science community to understand fundamental physical processes in solar and space physics. These missions make scientific discoveries that close knowledge gaps to advance the first part of the solar and space physics mission to explore our habitable cosmos.

LWS missions are driven by the scientific curiosity of the science community, informed by scientific advances needed to respond to space weather needs. These missions have targeted science goals that contribute to the understanding that ultimately leads to operational space weather prediction and forecasting. The LWS program has synergies with the NASA Space Weather Program that focuses on effective transition of space weather relevant knowledge, capabilities, technology, and techniques to operations.

The STP and LWS programs do not have any cost caps or programmatic strategies. These are implementation strategies of the major missions in the Heliophysics Division, and it is up to the division to determine how best to manage missions on a case by case basis.

LWS and STP Missions from the 2013 Decadal Survey: GDC and DYNAMIC

The highest-priority LWS and STP missions from the 2013 decadal survey, GDC and DYNAMIC, are currently in development (as part of the NASA program of record) and the science that these missions represent has only been amplified over the years.

There are four reasons to complete these missions in the next decade: First and foremost, they are needed for significant progress on critical, high-priority science focus areas related to the interactions between overlapping upper atmosphere systems. Second, they restore health to the community by balancing the overall Heliophysics Research Program that currently lacks upper atmosphere missions (see Figure 5-8). Third, these two missions, when executed simultaneously, act as a pathfinder for the heterogeneous constellation-class missions that are to follow in the next decade. Fourth, these missions have significant space weather science components as well as near-real-time measurement capabilities that are important for progress in space weather research. The next paragraphs address each of these reasons separately.

Science—As presented in Chapter 2, determining how the ionosphere and thermosphere respond to and process energy inputs from both large-scale waves originating in the lower atmosphere and particles and currents from the magnetosphere is central to understanding the heliophysics system. The combination of GDC and DYNAMIC provide key in situ and remote sensing observations of these energy inputs and quantify the multiscale response of the ionosphere and thermosphere to these inputs. These observations enable determination of the high-latitude ionosphere and thermosphere response to changing solar wind and magnetic energy inputs and how that response leads to plasma motion, neutral winds, and creation of coherent structures. The plasma and neutral population responses to these energy inputs are covered over a range of different scales, from local to global. These responses include the partition between chemical and dynamical processes that lead to effects such as enhancements of thermospheric density at LEO altitudes. GDC and DYNAMIC resolve how processes internal to the ionosphere and thermosphere redistribute mass, momentum, and energy in response to global-scale waves originating lower in the atmosphere. Importantly, the two missions determine the underlying causes of long-term changes in the planetary space environment.

Health of the community—With the loss of the ICON mission and the change of the GOLD and TIMED missions to infrastructure HSO missions, upper atmosphere (ITM) research has at its disposal only one ITM instrument on the space station (AWE). GDC and DYNAMIC restore some of the balance to the research strategy, allowing ITM research to renew and flourish.

Pathfinder missions—The next generation of solar and space physics missions, especially in the magnetosphere and ITM, are mostly implemented as constellations of heterogeneous spacecraft. This completely new type of scientific mission category has multiple spacecraft making different (in situ and remote) observations from different orbits tuned for the measurement needs. These mission characteristics come with significant new challenges. Not only does the constellation need multiple, different spacecraft to be developed, but often also multiple launches are required to reach the different orbits. Overcoming these challenges while keeping mission, instrument, spacecraft bus, and operations costs within reason requires new approaches to instrument manufacturing and testing, spacecraft bus development, as well as risk and quality assurance practices and requirements. The combined GDC and DYNAMIC missions form an important pathfinder for such heterogeneous constellation missions.

Space weather—Chapter 3 and the space weather subsection of this chapter outline the many significant contributions that GDC and DYNAMIC bring to understanding, monitoring, and predicting space weather. Chapter 3 identified space traffic management and collision avoidance at LEO to be among the highest-priority needs from space weather research. GDC and DYNAMIC contribute importantly to this key space weather scientific, societal, and technological challenge for the next decade.

Highest-Priority New STP Mission: Links

The highest-priority new STP mission for the next decade is represented by the notional "Links Between Regions and Scales in Geospace" (Links) constellation, pushing the boundaries of coordinated multipoint measurement technologies (see summary of technical and cost information in Appendix G). Links is a flagship-class systems science mission to discover the dynamic couplings and connections across regions and scales in the near-Earth space environment. This notional mission contributes to progress on all science themes in Chapter 2 by determining the combinations of fundamental processes (Section 2.2) that build up the complex dynamics between the solar wind and Earth's coupled magnetosphere–ionosphere systems (Section 2.1). The foundational understanding from a mission like Links may help assess the habitability of exoplanets (Section 2.3) as well as to build next-generation space weather applications (Chapter 3).

This bold constellation mission concept comprises two platforms for auroral and magnetospheric imaging along with 24 satellites making in situ observations in the magnetosphere. The auroral imagers provide unprecedented simultaneous coverage of the northern and southern auroral ovals, unraveling questions related to (a)symmetries between the two hemispheres. The magnetospheric imagers provide the first-ever portrayal of the tenuous plasma system engulfing Earth, as the fleet of 24 satellites resolve for the first time the striated plasma flows and structured magnetic fields providing ground truth for the global imagers (Figure 5-13).

The simultaneous conjugate auroral observations from the two hemispheres are provided by spacecraft in circular polar orbits that view both the auroral oval and the magnetotail transition region near the equatorial plane. The high (~20 km) spatial resolution of the imagers resolves the meso-scale auroral dynamics and energy deposition that close an important gap in the global energy circulation process. The dual imager system reveals asymmetries in energy deposition and auroral processes between the two poles, and how such asymmetries between the poles impact the magnetotail processes.

Each imaging spacecraft carries three energetic neutral atom (ENA) imagers that provide remote sensing observations of the magnetospheric ion populations. These images reveal for the first time the shapes, sizes, velocities, and pathways of these dynamic structures that are the main carriers of energy from the outer magnetosphere inward. The composition and spectral information define the role of ionospheric sources in magnetic storm processes.

This ground-breaking constellation will be the first ever to resolve magnetotail dynamics simultaneously along and across the magnetotail, allowing the spatial structure and the temporal evolution to be uncovered at the same time. The in situ satellites have mesoscale (0.5–1 R_E) spacing near their apogees, designed to resolve the flow channels and the associated magnetic flux bundles and filamentary current systems in the magnetotail as well as transient phenomena within and around the bow shock and dayside magnetopause. Each in situ spacecraft carries

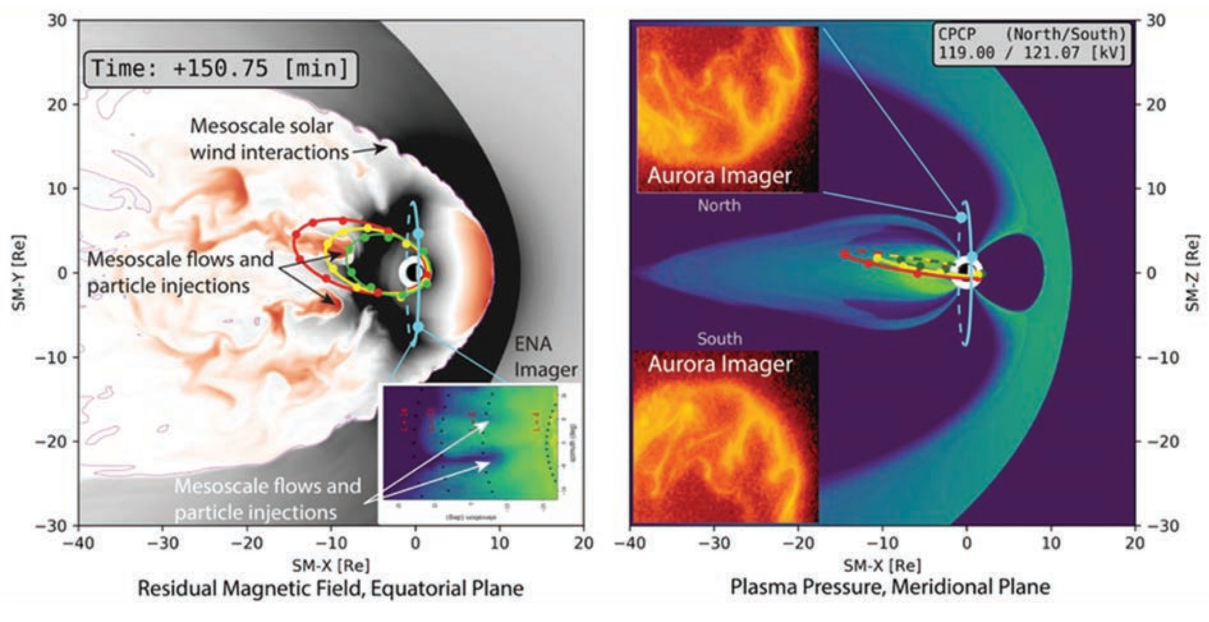

FIGURE 5-13 Illustration of the Links notional mission spacecraft orbit configuration in the magnetospheric equatorial and noon-midnight meridian planes, superimposed on a Grid Agnostic Magnetohydrodynamic for Extended Research Applications (GAMERA) global magnetosphere simulation.
SOURCES: Modified from Sorathia et al. (2020), https://doi.org/10.1029/2020GL088227. CC BY 4.0; Auroral images from the Department of Energy.

an instrument suite consisting of ion and electron plasma and energetic particle detectors and a magnetometer, enabling measurements of high-speed plasma flows, particle injections, magnetic field dipolarizations, and dayside transient plasma and magnetic field structures.

The notional Links mission responds to the primary objective of the STP mission line, to "understand fundamental physics processes from the Sun to Earth" with its scientific objective to determine the mass, momentum, and energy flow in the magnetosphere. It will advance understanding of the cross-scale and cross-regional coupling that directly feeds to broad scientific progress with applications beyond the terrestrial space environment. It is also expected to pinpoint key processes in the coupled system dynamics at Earth, thus its discoveries will enable operational space weather prediction and forecast models to take major leaps forward. As with all STP missions, Links would benefit greatly from international participation.

More details of this constellation-class mission are provided in the report of the Panel on the Physics of Magnetospheres in Appendix C. The cost information from the TRACE process for this mission is provided in Chapter 6 and Appendix G.

Recommendation 5-8: The highest priority for a new Solar Terrestrial Probes mission is one to investigate the system-level global coupling between the solar wind, magnetosphere, and ionosphere, while resolving mesoscale dynamics. This requires a heterogenous constellation mission that includes in situ measurements and remote sensing. If a science and technology definition team study is appropriate for the implementation, then it should be done early in the decadal survey interval in time to support development starting in fiscal year 2027.

Highest-Priority New Living With a Star Mission: Solar Polar Orbiter

The highest-priority new LWS mission for the next decade is a mission that focuses on the Sun's poles. The notional mission that underwent the TRACE process was the Solar Polar Orbiter (SPO), shown schematically in Figure 5-14.

SPO is an ambitious mission concept to image the Sun from a completely new place to answer fundamental questions about how the Sun generates its magnetic field and how the field drives solar activity and shapes the heliosphere over the course of the solar activity cycle. The SPO would be the first mission to image the extended polar regions of the Sun, focusing on the solar magnetic fields. Historically, solar observations have been made from the ecliptic plane (on which Earth orbits the Sun) and most often from the Sun–Earth line. ESA's Solar Orbiter is a notable exception, but even its measurements are limited to relatively small out-of-the-ecliptic viewing angles. The polar regions are key to understanding the cyclic behavior of solar activity and these regions are observable only from a high-inclination vantage point.

A mission to observe the solar poles is needed to establish how the Sun's differential rotation evolves from the equator to the poles, how the plasma convects at and near the poles, and what the strength and distribution of the magnetic field is at and near the poles. These measurements are critically important to constrain models of the solar magnetic dynamo and to understand the time-variable extension of the solar magnetic field into the interplanetary medium. SPO builds on results from previous missions. The Ulysses mission made several passes above the solar polar regions and recorded the solar cycle variability of the solar wind and magnetic field structures at high solar latitudes. However, focused on in situ observations, Ulysses did not resolve the solar sources of these fields and flows. While ESA's Solar Orbiter will eventually observe from a vantage point that is as much as 30° out of the ecliptic, it does not provide the kind of sustained observations necessary to make significant progress on these questions. Furthermore, SPO imagery provides an entirely new perspective on the corona and heliosphere by observing from well above the ecliptic plane. For example, SPO can determine the longitudinal structure of the streamer belt, radial and longitudinal extent of solar eruptions, and the longitudinal origins of fast solar wind streams.

SPO makes progress on all the science themes described in Chapter 2. By revealing details and variability of the magnetic fields at the solar poles, SPO data helps uncover the "solar magnetic field through the heliosphere" (Section 2.1). The SPO observations are crucial for the guiding question, "How is the Sun's global magnetic field created and maintained, and what causes its cyclical variations?" (Section 2.2). The SPO mission contributes to

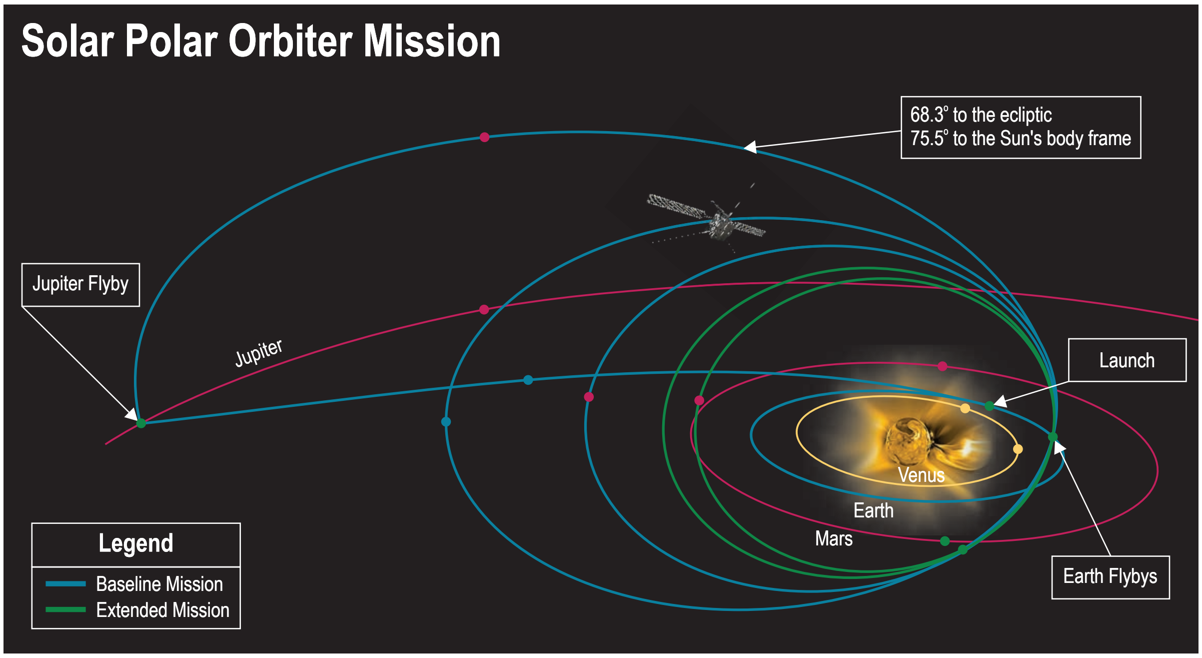

FIGURE 5-14 The Solar Polar Orbiter mission uses a Jupiter gravity assist and several Earth gravity assists to make unprecedented observations of the Sun's poles.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Sun image from Hassler et al. (2022), https://doi.org/10.3847/25c2cfeb.408d006f. CC BY 4.0.

"exploration of new environments" (Section 2.3), as very little is known of the dynamics of the solar poles. Prior missions to the giant planets have shown beautiful vortices such as those in the Jovian polar regions (Juno) and an intriguing hexagonal jet stream at Saturn's poles (Cassini). If such vortices or jets were found at the Sun's poles, they would likely play a critical role in determining the generation of magnetic fields in the Sun. As the solar magnetic field structure is the key driver for space weather (Chapter 3), the SPO mission has direct relevance for understanding long-term space climate evolution.

SPO responds to the primary objective of the LWS mission line, to "provide scientific understanding that leads to predictive capability." Specifically, the space weather advancements come through recording the first polar magnetograms over multiple solar rotations and simultaneous 360° longitudinal views of coronal structure, variability, and coronal mass ejections (CMEs). The comprehensive suite of instrumentation on SPO includes a compact doppler magnetograph, extreme ultraviolet (EUV) imager, white light coronagraph, ion electron spectrometer, ion mass spectrometer, heliospheric imager, and an energetic particle suite. The spacecraft uses planetary gravity assists to achieve a 3-year orbit that is >70 degrees out of the ecliptic plane, allowing extended periods of unobstructed observation of both the northern and southern solar poles. The mission lifetime spans at least one solar activity cycle. As with all LWS missions, SPO would benefit greatly from international participation.

More details of this out-of-the-ecliptic mission are provided in the report of the Panel on the Physics of the Sun and Heliosphere in Appendix B. Cost information from the TRACE process for SPO is provided in Chapter 6.

Recommendation 5-9: The highest priority for a new National Aeronautics and Space Administration Living With a Star mission is one to explore the solar polar regions to understand how polar magnetic fields and flows reveal the Sun's global dynamics and the mechanisms that underlie the solar dynamo and shape the solar activity cycle. A science and technology definition team study should be completed by approximately the middle of the decadal interval (i.e., before fiscal year [FY] 2029) in time to support mission development starting in FY 2029.

5.2.4 Integrated HelioSystems Laboratory and Scientific Progress

Data from the integrated HSL make substantial progress on all focus areas in Chapter 2. Advances in the focus areas will ensure progress on the guiding questions for each science and space weather theme.

The existing elements of the HSL (Figures 5-4 and 5-8) contribute to this scientific progress. However, transformational progress is only possible if these existing elements are augmented by the missions and projects in development and the new elements of the HSL that are recommended in this decadal for the next decade. Especially, major discoveries and groundbreaking new understanding hinge on the major STP and LWS missions proposed above.

Table 5-6 repeats the themes, focus areas, and guiding questions in tabular form for easy cross-referencing with Table 5-7, which shows how the missions and projects (both in development and recommended by this decadal) connect with the guiding questions and focus areas. Naturally, the larger resources reserved for flagship missions like GDC, DYNAMIC, Links, and SPO make progress on many more focus areas than, for example, cost-capped Explorer missions. The focused science made by the Explorer missions, achievable with a budget that is several times smaller than the broader flagship missions with larger hardware resources and science personnel, is nonetheless highly valuable and fills in gaps in the science progress that would not be covered otherwise.

While Tables 5-6 and 5-7 focus on science and the HSL, the integrated HSL also includes NOAA space weather operations. The link between the NOAA space weather operational missions and the space weather themes is presented in complete form in Chapter 3.

TABLE 5-6 Science: Explore Our Habitable Cosmos—Themes, Guiding Questions, and Focus Areas from Chapter 2

Guiding Question	Focus Area
Theme 1: Sun–Earth–Space: Our Interconnected Home	
1.1 How does our heliosphere function as a nested system?	1.1a Energy and momentum flow across and within the heliosystem parts 1.1b Dominant physical processes within system interactions 1.1c Interactions across large-scale regions and long timescales
1.2 How do heliosystem boundaries manifest themselves?	1.2a System impacts of magnetic boundary processes 1.2b Role of transition regions in system coupling 1.2c Interactions at plasma-neutral transition regions
1.3 How do the components of the Sun–Earth system interact with each other?	1.3a Magnetic connections across the Heliosystem 1.3b Multiple drivers and feedback mechanisms
Theme 2: A Laboratory in Space: Building Blocks of Understanding	
2.1 How is the Sun's global magnetic field created and maintained, and what causes its cyclical variations?	2.1a Flows and fields across all solar latitudes 2.1b Linkages of the interior field to the global heliosphere 2.1c Longitudinal variation of the dynamo and the field
2.2 How are explosive phenomena created and dissipated across the heliosphere, and what are the fundamental processes that contribute to the energy conversion?	2.2a Energy conversion in explosive events 2.2b Consequences of the aggregator of individual explosive events 2.2c Response of systems to explosive events
2.3 How do the fundamental processes govern the cross-scale coupling, and what are the global properties and consequences of these processes?	2.3a Cross-scale implications of magnetic reconnection 2.3b Cross-scale coupling through interactions between magnetic reconnection, turbulence, shocks, wave-particle interactions, and particle acceleration 2.3c Instabilities and waves with cross-scale consequences 2.3d Nature and consequences of coupling between ionized fluids and neutral fluids

TABLE 5-6 Continued

Guiding Question	Focus Area
Theme 3: New Environments: Exploring Our Cosmic Neighborhood and Beyond	
3.1 What can we learn from comparative studies of planetary systems?	3.1a Mass and energy flow processes driving planetary magnetospheres 3.1b Interactions of plasmas with solid body surfaces and atmospheres 3.1c Diversity of auroral processes
3.2 Why does the Sun and its environment differ from other similar stars?	3.2a Similarities and differences between solar and stellar dynamos 3.2b Implications of different solar and stellar flare rates, amplitudes, and distributions 3.2c Differences between the heliosphere and other astrospheres
3.3 What internal and external characteristics have played a role in creating a space environment conducive to life?	3.3a Role of a magnetosphere in planetary atmosphere evolution 3.3b Role of a magnetic field as a shield from external radiation 3.3c Implications of internal particle acceleration, trapping and loss

NOTE: The color scheme matches the color scheme for the science questions in Figure S-1.

TABLE 5-7 The Connection Between the Elements of the HelioSystems Laboratory (HSL) and the Themes, Questions, and Focus Areas in Table 5-6

	Theme 1: Sun–Earth–Space: Our Interconnected Home			Theme 2: A Laboratory in Space: Building Blocks of Understanding			Theme 3: New Environments: Exploring Our Cosmic Neighborhood and Beyond		
	GQ1.1	GQ1.2	GQ1.3	GQ2.1	GQ2.2	GQ2.3	GQ3.1	GQ3.2	GQ3.3
Program of Record: HSL Elements in Development									
Vigil	1.1a 1.1c			2.1c					
HERMES									3.3b
AWE						2.3b			
Carruthers									3.3a 3.3b
EZIE			1.3b			2.3b 2.3c			
Solar-C/EUVST	1.1a	1.2a 1.2b		2.1a 2.1b 2.1c	2.2a 2.2b 2.2c	2.3a 2.3b 2.3c		3.2b 3.2c	
SunRise					2.2a				
PUNCH	1.1a		1.3c		2.2b	2.3c			
TRACERS	1.1a	1.2a			2.2a	2.3a			
MUSE	1.1a	1.2a 1.2b			2.2a 2.2b 2.2c	2.3a 2.3b 2.3c		3.2b	
HelioSwarm						2.3b			

continued

TABLE 5-7 Continued

	Theme 1: Sun–Earth–Space: Our Interconnected Home			Theme 2: A Laboratory in Space: Building Blocks of Understanding			Theme 3: New Environments: Exploring Our Cosmic Neighborhood and Beyond		
	GQ1.1	GQ1.2	GQ1.3	GQ2.1	GQ2.2	GQ2.3	GQ3.1	GQ3.2	GQ3.3
DYNAMIC	1.1a 1.1b 1.1c	1.2b	1.3b		2.2c	2.3b 2.3c 2.3d			
IMAP	1.1a 1.1c	1.2a	1.3b			2.3b 2.3d		3.2c	
GDC	1.1a 1.1b 1.1c	1.2b	1.3b		2.2b 2.2c	2.3b 2.3c 2.3d			
New Elements of the HSL									
DASHI	1.1b	1.2b 1.2c	1.3a 1.3b		2.2c	2.3b 2.3c 2.3d			
FASR	1.1a 1.1b	1.2b 1.2c	1.3b		2.2a 2.2b	2.3a 2.3b 2.3c		3.2a 3.2b	
ngGONG	1.1a 1.1c	1.2c		2.1a 2.1b 2.1c				3.2a 3.2b	
SPO	1.1a 1.1b 1.1c		1.3a	2.1a 2.1b 2.1c				3.2a	
Links	1.1a 1.1b 1.1c	1.2a 1.2b 1.2c	1.3a		2.2a 2.2b 2.2c	2.3a 2.3b			
Supporting Elements of the HSL for Theme 3									
ESCAPADE							3.1b 3.1c		3.3a 3.3b
Venus Missions							3.1b		3.3a 3.3b
Uranus Orbiter							3.1a 3.1c		3.3a 3.3b 3.3c
PLATO								3.2b	
Juno							3.1a 3.1b 3.1c	3.2b	3.3a 3.3b 3.3c
Bepi-Columbo							3.1a 3.1b		3.3b 3.3c
Jupiter Icy Moons Explorer							3.1b		3.3a 3.3b 3.3c
Europa Clipper							3.1a 3.1b		3.3a 3.3b 3.3c

NOTES: The color scheme matches the color scheme for the science questions in Figure S-3. Acronyms provided in Appendix H.

5.3 DRIVE+: ENHANCEMENTS IN RESEARCH AND TECHNOLOGY

Supporting research and technology programs are essential elements for realizing the scientific potential of investments in spaceflight and ground-based projects. Broadly speaking, these are grant programs that support data analysis, theory and modeling, research infrastructure, technology development, and workforce development. The integrated HSL described in Section 5.2 provides the coordinated data needed to pursue the ambitious goals of the coming decade. To reach these goals, data need to be analyzed, combined with theory, and turned into scientific results. A vibrant and integrated research program is needed to support a healthy, productive workforce and the scientific advances they will produce.

The 2013 decadal survey took an important step toward integrating research programs by introducing the original DRIVE[12] concept (Box 5-1). DRIVE continues to be a powerful organizational tool for research and technology programs. Its multiagency nature builds on the strengths and investments of each agency, while reflecting the interagency cooperation needed to achieve decadal survey science goals.

This decadal survey recognizes the value in retaining the DRIVE organizational framework, but also recognizes that enhancements are required to realize ambitious scientific progress. In the next decade, the recommended program builds on the success of DRIVE with "DRIVE+," which includes recommendations for enhancements in four areas—workforce, collaboration and coordination, research tools, and technology development (Figure 5-15).

The DRIVE+ framework consists of recommendations that are responsive to new challenges while reflecting the emerging opportunities and the new ways of conducting scientific research that are required to make progress on the decadal survey themes (Chapters 2 and 3). The integrated HSL (Section 5.2) enables better coordination between a wide range of community facilities that produce data, including ground-based and space-based observatories. DRIVE+ works with the HSL, turning HSL data into scientific results.

In the next decade, the HSL is augmented with the Links and SPO missions, two new ground-based mid-scale projects (FASR and DASHI), ngGONG (important for science and space weather), and a flagship-level community science modeling program. The confluence over the past few years of HPC, AI, and the emergence of small satellites and associated technologies is also having an extraordinary impact on solar and space physics research. While these emerging technologies and techniques offer great opportunities, major scientific progress will require their efficient use and new tools and methods for managing and integrating heterogeneous multipoint/multiplatform measurements and the resulting large data sets. DRIVE+ provides the framework for realizing the scientific potential of these advances through enhancements to workforce development and cross-divisional and cross-agency coordination for enhanced research and technology programs.

BOX 5-1
DRIVE

DRIVE was introduced in the previous decadal survey as a multidecadal framework for organizing and enhancing agency research programs. Key achievements include three NASA DRIVE Science Centers selected in 2022, reorganization of technology programs and increased funding for suborbital and CubeSat missions, a boost to Research and Analysis programs (e.g., the Heliophysics Guest Investigator-Open program element), and the new National Science Foundation mid-scale infrastructure project line. Consistent with the midterm assessment (NASEM 2020), this decadal survey continues these efforts while evolving them to meet the needs of the coming decade.

[12] The 2013 solar and space physics decadal survey recommended, "implementation of a new, integrated, multiagency initiative (DRIVE—Diversify, Realize, Integrate, Venture, Educate) that will develop more fully and employ more effectively the many experimental and theoretical assets at NASA, NSF, and other agencies" (NRC 2013, p. 77).

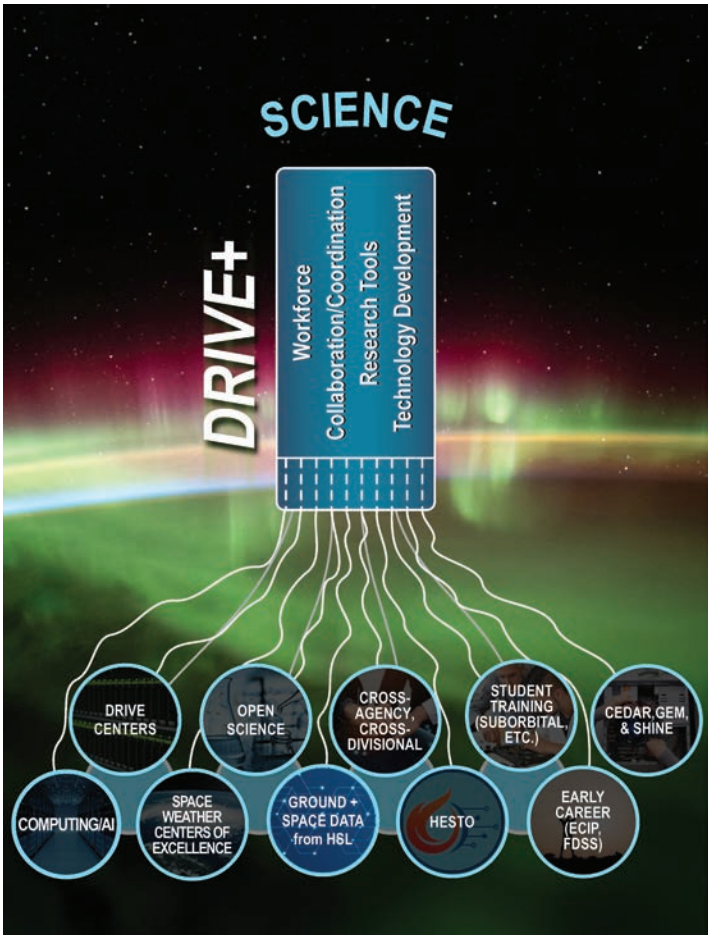

FIGURE 5-15 DRIVE+ includes enhancements in four areas: workforce, collaboration and coordination, research tools, and technology development.
SOURCES: Composed by AJ Galaviz III, Southwest Research Institute; Background image from NASA. Inset circle images: Drive Centers from ©Pixza/Adobe Stock; Open Science from ©totojang1977/Adobe Stock; Cross Agency/Cross Divisional from ©Yingyaipumi/Adobe Stock; Student Training from ©goodluz/Adobe Stock; Cedar, Gem, & Shine from ©AnnaStills/Adobe Stock; Computing/AI from ©frender/Adobe Stock; Space Weather Centers of Excellence from ©Artsiom P/Adobe Stock; Ground Space Data from HSL from ©Windawake/Adobe Stock; HESTO from NASA; Early Career from ©sutadimages/Adobe Stock.

5.3.1 Workforce of Tomorrow

Like many areas in modern science, solar and space physics requires a diverse set of tools and a workforce with a broad range of knowledge and skills. A sustained and productive workforce is an essential foundation for all scientific progress. Ultimately, it is the people who dream up new ideas; conceive and execute new missions, facilities, or models; and creatively analyze their data to advance science. A productive workforce is a healthy and diverse workforce that continues to evolve. The programs that support the current and future solar and space physics workforce form an essential element of DRIVE+.

Ongoing supporting research and technology elements important for building and training the workforce include graduate student fellowships (e.g., NSF Graduate Research Fellowships Program [GRFP], NASA's Future Investigators in NASA Earth and Space Science and Technology [FINESST]) and support for postdoctoral researchers (e.g., NASA's Postdoc Program and Jack Eddy Postdoctoral Fellowship) and early career researchers (NASA's Early Career Research program [ECIP], AFOSR Young Investigator Program [YIP]). Suborbital and

CubeSat programs, in addition to providing valuable data for science, are essential for providing hands-on training opportunities (Section 5.3.4). Materials to support future mission leaders are provided by the NASA SMD list of resources for PIs[13] and the PI LaunchPad Workshops, which were initiated in 2019 to provide better access and training for aspiring mission PIs.

Chapter 4 discusses the current state of the profession and includes recommendations for ensuring a sustainable workforce that meets evolving basic research and space weather needs. Those recommendations that fall into the DRIVE+ framework include the following: Recommendation 4-2, which details how the funding agencies can expand the reach of space physics in education to recruit students from diverse areas of study; Recommendation 4-3, which asks NSF to continue and expand support for the Faculty Development in geoSpace Science (FDSS) program in solar and space physics at colleges and universities; and Recommendation 4-4, which asks funding agencies to increase opportunities for researchers to lead summer schools, workshops, and other skill-building activities for undergraduate and graduate students.

5.3.2 Collaboration and Coordination

Different aspects of solar and space physics research are supported by different agencies, reflecting its interdisciplinary nature and the diverse types of data and tools required to advance the science. The integration of heterogeneous data sets and models, and the cross-divisional and cross-agency coordination required to enable it, are essential for addressing the science goals and space weather needs of the next decade.

Space Weather

Cross-agency collaboration in the field of space weather has advanced significantly; however, the December 2023 memorandum of agreement between agencies is a positive step, but needs to be followed by action (Section 3.3). Areas where further coordination would lead to a better use of resources, and improved outcomes, were identified in Chapter 3 and are not repeated here. However, the committee emphasizes the importance of space weather research priorities being informed by user-driven needs and outcomes. The space weather research recommendations relevant to DRIVE+ include the following: Recommendation 3-2 to NOAA and DoD to identify high-priority space weather research goals and develop processes to ensure communication of these priorities across NASA, NSF, NOAA, and DoD-DAF; Recommendation 3-3, which asks NASA and NSF to target their research programs to these prioritized research goals; and Recommendation 3-4 to NOAA to establish a space weather research program and partner with DoD to develop large-scale predictive space weather models that can meet the operational demands.

Combining Ground- and Space-Based Data Sets

Community interest in expanding, coordinating, or integrating instrument networks in support of systems science has been steadily increasing. Improvements in coordination are needed to make significant progress toward decadal science goals. For example, now that Inouye is online, good coordination between NSF and NASA is critical for realizing the scientific potential of combining ground- and space-based observations across the spectrum and in situ. The recent ISTP-Next report that grew out of a community-led grassroots effort expresses the coordination needs by stating that "the current uncoordinated and oftentimes fractured observational, analysis, and modeling activities are incompatible with the holistic system-of-systems approach that is needed to answer many of the outstanding science questions of this era" (ISTP-Next 2023). Recommendation 5-1 addresses the need for agencies to coordinate development and operations of ground- and space-based assets through strategic management of an integrated HSL. This is necessary but not sufficient; after the HSL data are collected, research support for their combined analysis is needed to turn data into scientific results.

Systems science methodology emphasizes a close integration of ground- and space-based assets because they observe different aspects of a single phenomenon. Use cases abound but with differing emphasis depending on

[13] "New Principal Investigator (PI) Resources," for Researchers, NASA, https://science.nasa.gov/researchers/new-pi-resources, accessed June 2, 2024.

subdiscipline. For instance, solar physics requires comprehensive remote sensing observations across the electromagnetic spectrum, as well as in situ observations of particles and fields, from multiple vantage points.

ITM and magnetospheric studies demand a combined data set registered to common coordinates. Data returned from space missions and ground-based facilities are currently managed by different agencies, or different directorates within an agency (e.g., at NSF). As a result, data formats and other aspects of archiving and distribution are not handled uniformly. Furthermore, the agencies prioritize different data sets in their strategies and decision-making. This creates artificial barriers and unnecessary risk at the proposal phase, in particular, to projects that seek a tight integration of space- and ground-based observations at the mission planning phase.

Agencies have started to recognize that combined assets can be more than the sum of their parts and are making efforts to improve coordination, such as NASA's HSO with data accessible through the Space Physics Data Facility (SPDF). NSF has invested in enabling joint analysis of ground magnetometers through the SuperMAG facility as well as the combined use of the individual SuperDARN radars. The HSL proposed in this decadal survey is the first attempt to bring together observations from heterogeneous sources and multiple platforms, essential for continued scientific progress.

Despite these positive steps, increased and sustained coordination will be required to achieve measurable progress in the identified research focus areas for the coming decade. This calls for new innovative approaches to obtaining, accessing, and analyzing diverse data sets. Recommendation 5-1 for an integrated HSL addresses the need for coordinated observations. Additional measures are needed to make scientific progress using these data.

Conclusion: Data analysis that combines ground- and space-based observations is essential for scientific advances in solar and space physics. Coordination among federal agencies (NASA, NSF, NOAA, and Air Force-AFOSR) is needed to enable data access and sharing of tools in a seamless and efficient way. Continued barriers to this kind of coordination limit scientific progress.

Recommendation 5-10: The National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) should expand and coordinate opportunities for carrying out scientific research that combines ground- and space-based observations. Grant funding opportunities should continue to enable and enhance joint analysis of ground-space data as appropriate. NSF and NASA should offer additional funding opportunities that support joint aggregation, assimilation, and analysis of ground- and space-based data and production and archiving of combined ground-space data products.

Cyberinfrastructure and Data-Driven Discovery

The explosive growth of data and computing capabilities over the past decade have ushered in a new era of data-driven discovery, impacting all areas of science, technology, and society. The integration of data science methods (e.g., AI, machine learning, big data, deep learning) into solar and space physics is rapidly changing the way researchers approach scientific discovery. This trend is only expected to accelerate in the coming decade with the proliferation of multipoint ground- and space-based measurements, remote sensing, and supercomputer simulations producing enormous amounts of data. These advances make it imperative for the solar and space physics community to develop a sustained cyberinfrastructure ("the hardware, software, networks, data and people that underpin today's advanced information technology"[14]) for collection, storage, and shared analysis of disparate data sets.

The community has started organizing at the grassroots level to respond to these challenges, while NASA and NSF have launched strategic programs to embrace and capitalize on this cultural shift.[15] NASA's Open

[14] "Cyberinfrastructure and Advanced Computing," Our Focus Areas, National Science Foundation, https://new.nsf.gov/focus-areas/cyberinfrastructure, accessed June 2, 2024.

[15] "Workshop for Collaborative and Open-Source Science Data Systems," Meetings, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, https://lasp.colorado.edu/meetings/sds-workshop, accessed June 2, 2024. "IHDEA and DASH Hybrid Meeting 14-18 October 2024," International Heliophysics Data Environment Alliance, https://www.cosmos.esa.int/web/ihdea/ihdea-dash-2024, accessed June 2, 2024. "Python in Heliophysics Community," PyHC, https://heliopython.org, accessed June 2, 2024.

Source Science initiative[16] endeavors to make publicly funded scientific research transparent, inclusive, accessible, and reproducible. Within the initiative, NASA has instituted a 5-year Transform to Open Science (TOPS) program dedicated to establishing a robust infrastructure to train scientists and researchers on the critical definitions, tools, and resources underpinning the open science culture and to provide participants at all career levels with recommendations on best practices. Since 2017, NSF has embraced "10 Big Ideas" to "define a set of cutting-edge research agendas and processes that are uniquely suited for NSF's broad portfolio of investments, and will require collaborations with industry, private foundations, other agencies, science academies and societies, and universities."[17]

Among the Big Ideas is "Harnessing the Data Revolution," which seeks to engage NSF's research community in the pursuit of fundamental research in data science and engineering. This is realized through three principal components: research that seeks convergence across NSF directorates, educational pathways that support a data science–literate workforce, and advanced cyberinfrastructure to accelerate data-intensive research.

The solar and space physics community can build on this Big Idea through a coordinated strategy among NASA Heliophysics Division, NSF Geospace Section, NSF Division of Astronomical Sciences, and relevant parts of NOAA. With an increasing emphasis on systems science in the next decade, combined use of data from all sources with efficient means to access and process it will become crucial. This includes combining ground- and space-based; scientific, operational, and commercial; solar, heliospheric, magnetospheric, and upper atmospheric observations to describe the entire heliospheric system of systems. Such a common, sustained cyberinfrastructure, providing a single point of entry to all solar and space physics data for the entire community, is critical and would serve multiple inter-related purposes.

NASA's Heliophysics Division has done a commendable job in collecting observations from the HSO into a common SPDF and Solar Data Analysis Center (SDAC), open to all researchers. However, this system needs a major update to ingest vastly increased data volumes and to provide modern tools that enable combined analysis of heterogeneous data sources. For example, sophisticated search engines that facilitate finding multimessenger coordinated data of specific events is not something that SDAC currently allows. In addition, solar and space physics scientific observations are being augmented by a fleet of satellites operated by NOAA (e.g., the Polar Operational Environmental Satellites [POES] and DSCOVR), other government organizations, and private industries. While many of these organizations are willing and able to provide data for scientific use, there is no coordinated activity to bring those data to formats and platforms easily usable by the research community.

Furthermore, ground-based infrastructure to monitor space and the upper atmosphere has a variety of ownership and operational models. While some data are collected to common databases (e.g., the NSF-funded SuperMAG ground-based magnetometer data collection facility, the SuperDARN radar network data distribution system, AMPERE LEO magnetometer data facility, and the Virtual Solar Observatory [VSO]), there is no coordination or resourcing to bring these assets to a common framework. This results in wasted time and resources when individual researchers repeat data collection and processing tasks and limits the use of these valuable data in studies addressing systems science questions. Resolving these challenges at NSF will require coordination across NSF directorates, including the MPS Division of Astronomical Sciences (AST) (solar) and the GEO Division of Atmospheric and Geospace Sciences (geospace).

While it may not be feasible to build a single data repository with all data, it is feasible to build a common cloud-enabled cyberinfrastructure that links to existing data sources. Cloud resources will enable the analysis to be done where the data reside, eliminating the need to move around large volumes of data. Projects such as HelioCloud[18] are already enabling such functionality, albeit with a limited scope. Such efforts need to be scaled up to include disparate observational and modeling data sets from across solar and space physics.

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[16] "Open Science at NASA," Science, NASA, https://science.nasa.gov/open-science, updated May 31, 2024.

[17] "10 Big Ideas for Future NSF Investments," National Science Foundation, https://scepscor.org/documents/nsf_big_ideas.pdf, accessed June 2, 2024; and "NSF's 10 Big Ideas," Special Report, National Science Foundation, https://www.nsf.gov/news/special_reports/big_ideas, accessed June 2, 2024.

[18] "Cloud Software for the Heliophysics Research Community," HelioCloud, https://heliocloud.org, accessed June 2, 2024.

In summary, cross-agency strategies for implementation of a common cyberinfrastructure for solar and space physics should address the following needs:

- Cloud-ready, flexible, and standardized data formats and archives that embrace the FAIR principles (findable, accessible, interoperable, reusable) and facilitate investigations based on coordinated use of ground- and space-based data sources.
- Decentralized solutions such as "federated cloud" (Aristotle Cloud Federation 2024; HPCwire 2021).
- Strategies for funding cloud-enabled workflows (e.g., addressing who pays for data storage and analysis).
- Sustained funding infrastructure to employ teams with highly specialized expertise in data management and software engineering.
- Means for attributing proper credit to data and software providers—for example, adopting a formal citation system for data and software (including digital object identifier creation); developing metrics that assess the impact of data sets and software tools (usage statistics, downloads, citations); and supporting open science initiatives (e.g., NASA TOPS) that value and acknowledge contributions of data and software providers.
- Sustained efforts that expand and integrate data assimilation, machine learning, and empirical modeling, which, along with the use of OSSEs, have been shown to enable scientific and applied advancements in the climate/weather community.
- Automated methods to alleviate the burden of data annotation and curation, including the use of AI methods to create labeled data for machine learning.
- Implementation of a framework for discovery and innovation—for example, opportunities that encourage innovation without anticipating a given outcome.

Conclusion: NASA has made important strides through its Open Source Science (OSS) and Transform to Open Science (TOPS) initiatives, and NSF has created synergistic opportunities through its Harnessing the Data Revolution (HDR) initiative. Existing data collection and sharing facilities (e.g., NASA SPDF and SDAC; NSF SuperMAG, SuperDARN, AMPERE, and VSO) provide essential science-enabling services, but there is a critical need to build modern tools enabling combined analysis of heterogeneous data sources. Realizing the full potential of emerging technologies will require cross-program/cross-agency collaborations, supported by substantial investments in cyberinfrastructure.

Recommendation 5-11: The National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA) should continue to support the development of modern cyberinfrastructure to enable effective sharing and utilization of heterogeneous data produced across the integrated HelioSystems Laboratory. Future investments should consider the following agency roles and approaches:

- **NSF is well positioned to take a leadership role in this activity because the agency has an established history of funding community cyberinfrastructure programs of this scope.**
- **The NSF Cyberinfrastructure for Sustained Scientific Innovation program could serve as a funding vehicle; early-stage proof-of-concept efforts can be funded through this and other programs that offer smaller grants.**
- **NASA Heliophysics Division should integrate data-storage and data-sharing facilities, such as the space physics data facility, virtual observatories, and mission science gateways, into the new cyberinfrastructure.**
- **Integration of data systems should include coordination with NOAA, which should invest in the capability to provide data in formats compatible with the research data.**

Cross-Divisional Coordination Within NASA and Within the National Science Foundation

Most space-based solar and space physics research at NASA is supported by the Heliophysics Division. The increasing focus on understanding planetary habitability and Earth's atmosphere and climate motivates new opportunities for cross-divisional collaboration on topics such as exoplanets, stellar activity, and particle acceleration (Astrophysics Division) and planetary magnetospheres and upper atmospheres (Planetary and Earth Sciences Divisions) (Figure 5-16). Opportunities for cross-divisional collaboration on missions and technologies are further discussed in Section 5.4.

NASA has recognized the need for multi-, cross-, and transdisciplinary research to address critical heliophysics science goals. As one example, the 2018 announcement of opportunity for Heliophysics Phase I DSCs addressed this as a central theme, calling for centers to "play a major role in enabling interdisciplinary science and innovative approaches.. . . Create a rich environment that provides valuable research and educational experiences for the broader community."[19] Recognizing the importance of the multidisciplinary characteristics of successful DSCs, proposers were expected to include a "talented, diverse, multi/inter/trans-disciplinary, and fully integrated team to execute the research program." These centers are already expanding the traditional sub-disciplinary boundaries within the Heliophysics Division, which has resulted in major scientific advances and novel methodology developments—for example, the ongoing development of the Multiscale Atmosphere–Geospace Environment (MAGE) model now available to the broader community via the NASA Community Coordinated Modeling Center (CCMC).[20]

Space weather research is also inherently interdisciplinary, because it covers the full chain of processes occurring from the Sun, through interplanetary space, to planetary magnetospheres and upper atmospheres, as well as the impacts on humans and technological systems in space and on the ground. The Space Weather Centers of Excellence selected in 2023 combine expertise from a broad range of solar and space physics, and in many cases, also from the AI and machine learning research communities. These investments expand the solar and space physics community into the information sciences area and foster engagement with organizations developing or using the space weather information (e.g., NOAA, companies developing space weather products, and the space weather user community).

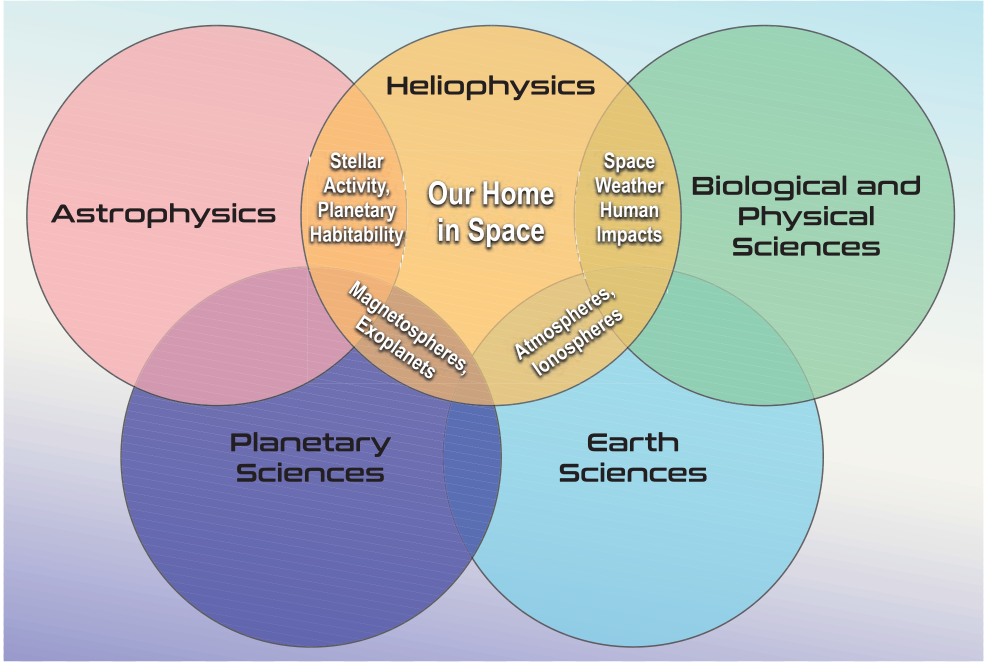

FIGURE 5-16 Examples of cross-divisional science interests at the NASA Science Mission Directorate.
SOURCE: Composed by AJ Galaviz III, Southwest Research Institute.

[19] "Amendment 24: DRAFT B.13 DRIVE Science Center Call Released for Community Comment." NASA Science Research website, https://science.nasa.gov/science-research/for-researchers/roses/amendment-24-draft-b13-drive-science-center-call-released-community-comment, updated May 22, 2023.

[20] "MAGE." Model Catalog, Community Coordinated Modeling Center, https://ccmc.gsfc.nasa.gov/models/MAGE~0.75, accessed June 2, 2024.

Solar and space physics is poised to provide connections between the different disciplines to enable transformational scientific progress. The guiding questions from Theme 3 (Section 2.3) are intrinsically interdisciplinary. Solar and space physics research has already provided new insights into the different planetary magnetospheres. The Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) mission has shown how a smaller magnetosphere in a denser solar wind responds on shorter timescales than at Earth. Orbiting missions at Saturn (Cassini) and Jupiter (Galileo, Juno) have shown how plasma sources from moons and rings plus strong coupling to the planet's rotation (via ITM processes) produce large magnetospheres with extensive plasma disks, strong aurora, and, particularly at Jupiter, intense radiation belts. The fundamental processes at work across all planetary systems are thought to be similar (see Section 2.2), but as the magnetic field, plasma density, and other environmental conditions vary by orders of magnitude, their relative importance and impacts can be vastly different. The expertise of the solar and space physics community in these areas is invaluable for understanding these remote systems covered by sparse observations. Comparison of Earth's magnetosphere and ionosphere to those of other planets, and the Sun and heliosphere to other stars and their astrospheres, will answer questions about the potential habitability of other systems. As more exoplanets are discovered, the parameter space of natural space plasma laboratories is expanded. Moreover, a complete system-level understanding of the coupling and interactions of the Sun–Earth system (see Section 2.1) can only be obtained by comparing and contrasting results from systems with different parameter regimes and environments.

NASA Heliophysics is a participant in several cross-divisional or multidisciplinary efforts such as the Exoplanets Research Program and Habitable Worlds program elements. There is considerable community interest in expansion of such opportunities, demonstrated, for example, by grassroots activities such as the Whole Heliosphere and Planetary Interactions initiative and the recently initiated NSF Geospace Environment Modeling (GEM) focus group "Comparative Planetary Magnetospheric Processes." At the intersection of solar and space physics and Earth sciences research, modeling studies (e.g., Whole Atmosphere Community Climate Model-eXtended [WACCM-X]) have revealed that this significant change in ITM affects ozone chemistry as well as atomic hydrogen production and escape, which in turn affects the structure of the exosphere and its charge-exchange coupling to ions in the plasmasphere and magnetospheric ring current. (See also Section 5.4.4.)

At NSF, solar and space physics is supported from multiple divisions and directorates (see Box 5-2 and Section 5.3.3), illustrating the interdisciplinary nature of the field. Moreover, the broad mandate of NSF facilitates

BOX 5-2
Solar and Space Physics at the National Science Foundation

At the National Science Foundation (NSF), solar and space physics encompasses three different divisions: the Geospace Section of the Division of Atmospheric and Geospace Sciences (AGS) under the Directorate for Geosciences (GEO) and the Division of Astronomical Sciences (AST) and Division of Physics (PHY) under the Directorate for Mathematical and Physical Sciences (MPS). As of January 2024, AGS has been split into three clusters—the Atmosphere Cluster, the Geospace Cluster, and the Infrastructure Cluster—to "reflect the trans-disciplinary nature of science as it is increasingly conducted today in the research community" (Johansen 2024). Ground-based solar physics research is spread across two divisions in different NSF directorates (MPS/AST and GEO/AGS). For example, the NSO is supported through AST, the NCAR support for HAO comes from AGS, and the Goode Solar Telescope and EOVSA are supported by the Geospace Section of the AGS. The geospace facilities portfolio resides entirely under the Geospace Section of AGS, as do the strategic programs Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR), Geospace Environment Modeling (GEM), and Solar, Heliospheric, and Interplanetary Environment (SHINE), and the Solar-Terrestrial program. The Office of Polar Programs also provides critical logistical support for instrumentation in Antarctica and works with NASA's balloon program to support balloon-based solar and space physics research.

NOTE: This box was updated to accurately reflect solar and space physics activities at NSF.

transdisciplinary research spanning areas that are outside the field of space science, connecting space plasma research to that of laboratory plasmas and energy production; theory and modeling in solar and space physics with mathematical, statistical, computational, and information sciences; and, as an emerging topic, connecting NSF's basic research endeavors with the applied field of space weather. NSF has been proactive in supporting multidisciplinary efforts—for example, through a variety of space weather calls and by enabling community-organized efforts such as the Comparative Planetary Magnetospheres focus group mentioned above. Nevertheless, some areas of research near the boundaries can fall through the cracks, such as outer heliosphere and planetary sciences, neither of which seem to find a home in either geosciences or solar physics.

Recommendation 5-12: The National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) should actively contribute to a cultural change that would better foster cross-divisional research. Specifically, they should increase support for cross-divisional research by

- **Gearing research and data analysis programs toward better supporting cross-disciplinary projects. Mechanisms could include stating interdisciplinary goals in proposal calls, explicitly identifying calls that may span multiple divisions or directorates and improving the review process—for example, by broadening the panelist expertise.**
- **Initiating and funding interdisciplinary workshops to advance and develop cross-disciplinary collaborations.**
- **Initiating and funding NASA Science Mission Directorate (SMD)-wide opportunities for cross-disciplinary "Centers of Excellence" that would combine multidisciplinary teams to address cross-disciplinary research questions spanning across SMD divisional boundaries.**

Although these opportunities for expansion are valuable and would benefit the entire scientific community, it is important that these efforts to not take resources away from the core of solar and space physics research because there are still critical unanswered questions about the heliosphere and the basic physical processes at play.

Support by multiple divisions at the NSF (see Box 5-2) has sometimes been advantageous to solar and space physics. For example, funding is available from multiple NSF divisions for both researchers and different institutes, offering more diverse opportunities. Inouye is an excellent example of a major research facility that was supported both by AST and GEO. On the other hand, there may be significant benefits in consolidating solar, heliospheric, space physics, and space weather science within a single division. These include the ability to develop and enable a single strategic vision, better advocate for solar and space physics within NSF, enable better integration between ground-based facilities and programs, provide better interfaces to other space- and ground-based "system components," enable efficiencies and opportunities in proposal submission and review, and enable a single NSF entity to coordinate with other agencies and to provide a consolidated interface to national and international space weather science.

The 2013 decadal survey and its midterm assessment highlighted challenges related to the fragmented organizational structures at NSF, and those have become even more pressing in recent years. The astronomy and astrophysics decadal surveys have historically provided recommendations to AST for ground-based solar physics. However, in 2020, the astronomy and astrophysics decadal survey narrowed its scope to solar physics done in the service of astronomy. Thus, the AST division needs to respond to two decadal surveys (astronomy and astrophysics, solar and space physics), released at different times, to fully serve the solar community.

Additionally, as discussed in Chapter 4, there are challenges associated with identifying members of the solar and space physics community, and thus in obtaining accurate demographic information of the profession. Different terminology used by NASA (Heliophysics) and NSF (Geosciences and Astronomical Sciences) causes confusion in communicating the science to a broad audience and leaves solar and space physics without a clear identity in the public mind (e.g., the solar eclipse of 2024 was mostly identified as an astronomical event by the press). The different organizational structures can leave gap areas and make it more difficult to coordinate across agencies, especially in areas that deal with systems science problems spanning a broad range of disciplines. The new space weather mandate for the NSF (see Chapter 3) is at an institutional level, encompassing multiple divisions, which makes it more challenging to identify a clear point of contact.

Recommendation 5-13: The National Science Foundation (NSF) should address the challenges that arise from having the subdisciplines of solar physics, heliospheric physics, geospace sciences, space weather, and plasma physics managed within different directorates and divisions. NSF should conduct a study to examine possible organizational structures within the foundation that would serve these disciplines in an optimal way. The study would examine

- **Potential advantages and disadvantages of creating a single new division covering all fields of solar and space physics;**
- **Other solutions for addressing challenges arising from the organizational separations;**
- **Practices that ensure adequate support for all research areas and enable convergent research; and**
- **The challenges associated with incorporating recommendations from multiple decadal surveys within a single division or section.**

5.3.3 Enhancements in Science Support

Much of solar and space physics scientific research is supported by NASA and NSF R&A programs. At NASA, the annual Research Opportunities in Space and Earth Science (ROSES) solicitation invites proposals for a variety of research program elements across all science divisions. These support basic research, including, but not limited to, theory and modeling (e.g., Heliophysics Theory, Modeling and Simulation [HTMS]), analysis of data from currently operating missions (HGIO), LWS research programs, space weather R2O, and support for early career scientists. As detailed above, NSF funds solar and plasma physics out of the MPS Directorate and geospace research out of the GEO Directorate. Annual summer workshops supported by the GEM, CEDAR, and SHINE programs are a focal point for many in the community and are an important forum for graduate students and early-career researchers to learn and connect with other scientists.

In 2013, NASA Heliophysics reorganized its R&A programs, increasing the number of program elements from six in 2013 to seventeen in 2023. In general, these varied research programs have been highly successful and are routinely updated to foster new opportunities (e.g., recent Heliophysics Data Environment Enhancements [HDEE] and Heliophysics AI/ML Ready Data [H-ARD] elements, and the separation of technology programs into several more targeted elements such as Heliophysics Low Cost Access to Space [H-LCAS], Heliophysics Flight Opportunity Studies [H-FOS], and Heliophysics Flight Opportunities for Research and Technology H-FORT]). At NSF, a new solicitation, "Collaborations in Artificial Intelligence and Geosciences" (CAIG) was released in early 2024. However, some recommendations from the 2013 decadal survey (reaffirmed by the midterm assessment) have still not been realized. These include a joint NSF/Department of Energy (DOE) program on laboratory plasma science, adequate support for subjects falling outside of AST or AGS (e.g., outer heliosphere), and explicit collaboration with NASA on the DSCs.

DRIVE+ includes enhancements and updates to agency research programs in response to continuing challenges, such as the continued fallout from the COVID-19 pandemic, increases in inflation and other budget pressures, and new opportunities such as new tools in data science and the move to open science.

Data Products and Validation for NASA Infrastructure Missions

A major development since the 2013 decadal survey is the creation of an infrastructure mission category for the HSO (Section 5.2.1). These extended missions receive funding only for mission operations, data validation, and archiving, but not for carrying out scientific research.[21]

The community has voiced a lack of understanding of the process and raised concerns about the potential impacts of moving missions to the infrastructure category. In particular, the funding provided to infrastructure missions for data products does not seem consistent across missions, and there is confusion about the extent to

[21] Definition from NASA, 2023, "2023 Heliophysics Senior Review Call for Proposals," https://lasp.colorado.edu/galaxy/download/attachments/1900656/2023%20Heliophysics%20Senior%20Review%20Call%20For%20Proposals%20FINAL.pdf.

which scientific analysis can be supported by the mission funding (see also the 2024 Heliophysics Advisory Committee Report [NASA 2024b], which includes findings and recommendations on this topic), because part of data validation is always achieved through scientific analysis. These decisions communicate NASA's prioritization of science carried out by the broader research community rather than by the mission science team (Leisner 2024). While engagement of the broader community through guest investigator programs is commendable and expands the reach of each mission, it is essential to involve the mission science teams who understand instrument operations and can validate the data. Early career researchers often play an integral role in producing and validating mission data products; their participation is enabled by mission funding that also supports their own scientific research, necessary for advancing their careers.

Recommendation 5-14: For missions that are moved to the infrastructure category, the National Aeronautics and Space Administration should ensure that sufficient funding is provided for mission teams to calibrate and process data to Level 2 (calibrated data products that are in physical units, appropriate for use by the rest of the science community), deliver to the Space Physics Data Facility, and carry out scientific validation.

Realizing the Scientific Potential of Archival Data

In addition to the increased number of infrastructure missions for which scientific data analysis is not supported as part of the mission funding, some Heliophysics Division missions have ended their operations. These include Imager for Magnetopause-to-Aurora Global Exploration (IMAGE 2000–2005), Van Allen Probes (2012–2019) and its supporting BARREL balloon project (2013–2020), RHESSI small explorer (2002–2018), and ICON, which achieved full mission success at the completion of its primary mission (2019–2022). Together with the other integrated HSL components, significant amounts of high-quality data produced by these missions would form a valuable part of the HSL archive.

As many of the (combinations of) observations from the past and presently operative missions form unique data sets that will not be available in the foreseeable future, there is an acute need for program elements that support the analysis of archival data. This is important for both basic science research and space weather research. Recommendation 3-4 proposes that NOAA establish a new space weather research program that could support such analysis. At NASA, the HGIO program only supports analysis of currently operating missions, while the Heliophysics Supporting Research (HSR) program element encourages projects that combine data analysis with a theory or modeling component. While the combination of observation and theory/modeling is not strictly required, NASA has communicated—and the community broadly believes—that proposals not including both elements have lower priority for selection. A NASA presentation to HPAC in February 2024 stated as follows:

> Investigations focused primarily on data analysis of currently operating HSO missions may be more suitable for HGIO. Investigations that include only theory, modeling and/or simulation may be better suited to HTMS . . . proposals better suited for other programs but submitted to HSR may have a lower priority for funding. (Koehn 2024)

Conclusion: A significant amount of archival data has not been fully analyzed, leading to an under-utilization of prior investments to make scientific advancements and inform new missions and models.

Recommendation 5-15: To maximize the scientific return on previous investments, the National Aeronautics and Space Administration (NASA) should provide expanded opportunities for scientific research that uses archival data alone, without also requiring data from NASA infrastructure missions, currently operating missions, or a theory or modeling component. This could be achieved by expanding existing programs or creating a new heliophysics data analysis program element that would support data analysis projects.

Sustaining Robust Research Programs

The integrated HSL (Recommendation 5-1) and enhanced cyberinfrastructure (Recommendation 5-11) will offer new opportunities for ground-breaking research in the next decade. Robust support for research programs will ensure that the community can take advantage of improved access to new data new analysis tools and novel techniques.

It is important to ensure that the awarded grants are sized appropriately for the increased research costs, be they driven by inflation, increased student stipends and salaries, or auxiliary tasks expected of the team. Inflation reached a high of 7 percent in 2021 and remains at 3.5 percent as of the time of this report. Graduate student stipends have also increased at many institutions as the cost of living has risen.[22]

As agencies take positive steps toward open science goals, the additional tasks needed to meet the open science requirements increase the nonscientific workload for each grant. Providing research products in an open format with long-term availability and useability generates both monetary and personnel costs. The TOPS requirement is particularly onerous and expensive for theory and modeling grants. Specifically, open-source software releases, documentation, code maintenance, data management, and long-term storage all require significant additional resources and an expert workforce. Many, especially smaller, institutions do not have existing personnel and support structures for open science, and grant holders are left to find individual solutions, leading to researcher time being used for operational tasks. While the decadal survey committee generally supports NASA Heliophysics Division efforts to transition existing software to open source, the increased costs need to be compensated for in new grants.

> *Conclusion: It is critical to ensure that the work required to carry out individual research projects is adequately funded. The size of grants needs to be commensurate with increased costs such as those owing to inflation and increases in requirements on grantees.*

In addition to increased costs for individual grants, increases in proposal pressure can lead to decreased success rates. According to a recent report to HPAC, NASA saw a large increase in the number of proposals for some R&A programs in 2023 (Koehn 2024). While the average success rate for research proposals has remained at about 25 percent between 2016–2022 (Koehn 2024), a recent drop in selection rates for ROSES-23 (e.g., 14 percent for HSR and 17 percent for Heliophysics Flight Opportunities Studies [HFOS]) causes concern. Such concerns are amplified by other developments that have the potential to increase proposal pressure, such as recently announced changes to the Heliophysics Internal Scientist Funding Model program that provided funding for civil servants to carry out directed work and the transition of more NASA missions to the infrastructure category. The decadal survey committee is concerned that the scientific research using infrastructure missions will lead to increased proposal pressure for research elements such as HGIO, thus it would be beneficial to evaluate the impacts of these decisions in the next decadal survey midterm assessment.

A survey of grant writers found that success rates below 20 percent are likely to drive at least half of the active researchers away from federally funded research (von Hippel and von Hippel 2015). One article suggests that with success rates below 18 percent, decision-making becomes arbitrary (Kamerlin 2022). Low success rates are particularly detrimental for researchers, who are fully supported by external grants: if each 3-year grant funds one-third of an annual salary, the researcher must have funding equivalent to three active grants at any given time. If some of this funding comes from grants where the researcher is a co-investigator (Co-I), then the number of active grants is likely to be higher. Thus, for an average success rate of 15 percent, the researcher must submit 5–6 PI proposals or a higher number of proposals as PI and Co-I per year. An average success rate of 25 percent lowers this to 3–4 PI proposals submitted per year. Noting that proposal preparation can take hundreds of hours, writing five proposals annually amounts to at least 25 percent of the researcher's notional work time, which inevitably leads to lower scientific output. At academic institutions, grants often support graduate students and postdoctoral researchers. Low success rates may reduce opportunities for career development and have a negative impact on the workforce.

[22] See, for example, Nietzel (2022).

Conclusion: The proposal success rate is a good metric for assessing adequate funding levels and balance between different research program elements. A healthy proposal success rate is 25 percent or better.

Recommendation 5-16: The National Aeronautics and Space Administration (NASA) Heliophysics Division's research program should be augmented to maintain a typical proposal success rate of at least 25 percent and to increase grant sizes to account for cost increases owing to inflation and open science requirements. In the longer term, NASA should conduct an analysis to determine the appropriate size for research grants, taking into consideration typical salaries in the field, how people are funded, how many grants is a reasonable expectation for each person to have, grant duration, and the particular challenges of open source requirements for theory and modeling.

Although the focus of previous recommendations is on NASA research programs, these considerations apply to research programs at all the agencies. Proposal success rates specific to solar and space physics at NSF are not available to the committee or the public, thus it is difficult to assess whether the level of funding is adequate. It would be valuable if NSF and NOAA could similarly assess whether the grant size and proposal success rates for their research programs meet current needs.

Support for Theory and Modeling

Theory and modeling (T&M) are an integral part of heliophysics research (Section 5.2). The heliosphere is vast; in situ measurements are only available at a small number of locations at any given time, and remote sensing techniques provide only a glimpse of the global context. T&M, therefore, play a critical role in driving intuition, interpreting data, and motivating new measurements by making predictions. In addition, like other research fields that have a significant applied component, heliophysics relies on numerical modeling for forecasting and mitigation of space weather hazards.

Section 5.2 describes a new flagship community science modeling program that is part of the HSL; the community science models are included in the HSL because they are a resource for the community to obtain modeling data. DRIVE+ supports smaller-scale T&M efforts through grant programs, which enable smaller groups of researchers to tackle targeted problems.

The heliophysics T&M community leverages HPC facilities provided by multiple government agencies. NASA research grant proposals have the option of including a High-End Computing (HEC) allocation request for supercomputers supported by the NASA Advanced Supercomputing (NAS) Division. These allocations are granted upon proposal selection and can be extended as needed during the project's period of performance. NSF provides HPC resources to the U.S. research community via two avenues. Anyone with NSF funding can request an allocation on NCAR supercomputer facilities.[23] NSF also supports many academic supercomputers in the United States. Researchers can request an allocation via the NSF-sponsored Advanced Cyberinfrastructure Coordination Ecosystem: Services and Support (ACCESS) program. Furthermore, DOE owns 4 of the top 10 supercomputers in the world (according to the November 2023 TOP500 list[24]) and allocates a portion of their resources to the U.S. research.

While all these HPC facilities are available to the heliophysics T&M community, their limited resources are shared with many other scientific communities. Large allocations are highly competitive, and particularly challenging, because proposers must demonstrate their ability to make efficient use of a significant fraction of the HPC resource (e.g., demonstrate scalability with increased number of cores). Only a few heliophysics computational modeling codes achieve this efficiency because the development of such research software requires a highly specialized workforce and sustained funding to retain it. As a result, the community is not able to benefit from the full capacity of the existing national HPC resources, which limits transformative modeling-enabled advances in heliophysics research. A well-funded and long-term T&M program is necessary to overcome these technical barriers.

[23] The new NCAR Derecho supercomputer, with nearly 20 petaflops peak performance, entered production at the beginning of 2024.
[24] "November 2023," Lists, TOP500, https://www.top500.org/lists/top500/2023/11, updated November 2023.

Historically, T&M have been supported by the funding agencies (NASA, NSF, Air Force-AFOSR, NOAA) via a range of programs spanning from regular grants to large-scale projects that fund a team of scientists. The modeling needs for space weather were discussed in Section 3.3.4, and Recommendation 3-4 recommends that NOAA and DoD partner to develop large-scale predictive models. The hierarchy of the NASA T&M programs is shown in Figure 5-17, including the new, recommended flagship community science modeling (CSM) program (see Section 5.2).

Having a range of funding as well as targeted opportunities from the different agencies are essential for maintaining a healthy and sustainable T&M research program. For NSF, this includes base grants and GEM, CEDAR, and SHINE grants, through the larger-scale Advancing National Space Weather Expertise and Research toward Societal Resilience (ANSWERS) and Next Generation Software for Data-driven Models of Space Weather with Quantified Uncertainties (SWQU) programs. For NASA, this includes HTMS and LWS strategic capabilities through the larger-scale DSCs and Space Weather Centers of Excellence. Other essential opportunities target different parts of the community demographics, such as the NASA and AFOSR early-career programs.

Conclusion: The decadal survey committee supports the efforts of the funding agencies to provide opportunities for theory and modeling projects at a range of individual project sizes. It is critical to retain this variety to allow a full spectrum of theory and modeling research from pure theory (requiring support for individual researchers, graduate students, or postdocs) to large-scale model development (requiring support for large groups of scientists and other professionals—for example, research software developers).

The NASA HTMS program deserves a special mention because it was established to fill a specific niche to enable theory and modeling research carried out by relatively small teams. The program is also rather unique in providing support for purely theoretical efforts at a significant level. However, because HTMS grant sizes have never been adjusted for inflation or for increased complexity of model development (due to the evolving HPC landscape, including advancements in both HPC software and hardware), the HTMS program alone cannot respond to all current needs.

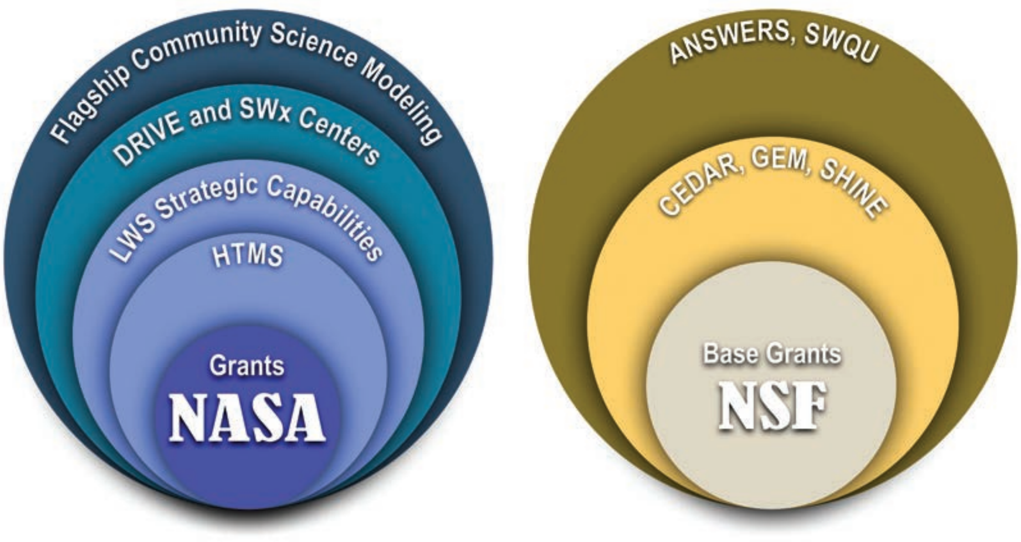

FIGURE 5-17 A hierarchy of funding opportunities for theory and modeling (T&M) research is critical to sustaining a healthy and productive overall solar and space physics research program. The NASA hierarchy of T&M funding programs is shown, including the new recommended flagship community science modeling (CSM) program (Section 5.2). The National Science Foundation (NSF) program shown covers the programs offered through the GEO program.
SOURCE: Created by AJ Galaviz III, Southwest Research Institute.

Conclusion: The HTMS program was established to cover a variety of theory and modeling projects from pure theory to model development. The HTMS grant size has never been adjusted for inflation or increased complexity of model development. Therefore, HTMS no longer serves the originally intended purpose efficiently.

The inclusion of T&M early in the formulation of NASA missions is also critically important because much of the scientific research in solar and space physics relies on the synthesis of observations and modeling. This is especially true for systems science objectives. This inclusion happens naturally in Explorer-class missions where the PIs build their teams to accomplish the mission objectives. The focus of the AO for directed missions is weighted toward instrument selection, and instrument teams are not well-positioned to include adequate mission-level T&M support in their proposals. Interdisciplinary scientist (IDS) programs—for example, like that associated with GDC[25]—provide an excellent mechanism for incorporating T&M into missions. However, it is crucial that T&M are part of the early mission formulation, ideally, from the pre-formulation stage when the science objectives are being defined. This early identification would ensure that T&M needs are well formulated by the time IDS teams are selected.

Conclusion: Theory and modeling are important components of solar and space physics missions of all sizes. In the case of Explorer-class missions, the science team is responsible for identifying these needs and including them in its proposal. A clear mechanism is needed for ensuring that strategic missions incorporate these elements early in mission planning stages.

Recommendation 5-17: The National Aeronautics and Space Administration (NASA) should ensure that theory and modeling needs are identified early in the pre-formulation phase for strategic (Living With a Star and Solar Terrestrial Probes) missions—for example, as part of a science and technology definition team. NASA should then determine the appropriate mechanisms for filling these needs. Selecting interdisciplinary scientists through open competition to join the mission team is one possible way to accomplish this.

The DSCs form a key element of the DRIVE initiative recommended by the 2013 decadal survey and reaffirmed by its midterm assessment. However, while the recommendation states that "NASA and NSF together should create heliophysics science centers" (NASEM 2020, p. 87), the program was implemented by NASA alone (with some behind-the-scenes input from NSF), and later in the decade than originally recommended. The NASA DSCs were competed in two phases with nine Phase I proposals selected in December 2019 and three out of these nine selected for Phase II in February 2022.

The three DSCs currently in Phase II are the Center for Geospace Storms (CGS), Consequences of Flows and Fields in the Interior and Exterior of the Sun (COFFIES), and Solar wind with Hydrogen Ion charge Exchange and Large-Scale Dynamics (SHIELD). These three centers engage in interdisciplinary scientific research, model development, communications, outreach, workforce development, and various other broadening impacts activities. All three DSCs are currently in the second year of Phase II, and the next class of DSCs is expected to start when the current ones are completed. The ongoing DSCs are already enabling research that would not be possible within the regular grants program because it requires relatively large teams. The DSC program fulfills a recommendation from the 2013 decadal survey and continues to be an important element of DRIVE+ in the next decade (Figure 5-15). Because the DSC program was implemented relatively late in the previous decade, it is expected that, around the time of the next midterm assessment, there will be lessons learned that could be taken into account in the future implementation. The NASA Space Weather Centers of

[25] "Amendment 5: Final Text and Due Dates for B.15 the Geospace Dynamics Constellation Interdisciplinary Scientists Program," NASA Science for Researchers, https://science.nasa.gov/researchers/solicitations/roses-2021/amendment-5-final-text-and-due-dates-b15-geospace-dynamics-constellation-interdisciplinary, updated September 11, 2023.

Excellence program was implemented even later, and there is a similar expectation of lessons learned by the time of the midterm assessment.

While different agencies may have different constraints, the DSC program would benefit from enhanced collaboration between NASA and NSF. Potential NSF contributions could be involvement by NSF facilities (e.g., by providing expertise on data usage) or by leveraging NSF's strengths in broadening impacts activities.

Recommendation 5-18: To ensure their continued success, the National Aeronautics and Space Administration should review the structure of DRIVE Science Centers program and Space Weather Centers of Excellence program around the time of the midterm assessment. This could be either in conjunction with the midterm assessment or as a separate study feeding into the midterm assessment.

Laboratory Space Plasma Advancing Solar and Space Physics

Laboratory plasma physics has made useful contributions to understanding of space plasmas. Several laboratory experiments have facilitated comparisons with solar and heliophysics conditions, enabling direct comparisons with solar and space physics observations and models. Several laboratories were at the forefront of this effort; the Line-Tied Reconnection Experiment (LTRX) plasma physics facility at the University of Wisconsin, Madison, was built to investigate ideal and resistive magnetohydrodynamic instabilities for various boundary conditions and equilibria. This experiment is suitable for solar physics because the boundary conditions are similar to those in the solar atmosphere. The Facility for Laboratory Reconnection Experiments (FLARE) at the Princeton Plasma Physics Laboratory (PPPL) is an intermediate collaborative user facility whose focus is on magnetic reconnection processes.[26] The Basic Plasma Science Facility (BAPSF) at the University of California, Los Angeles, is a national facility for fundamental plasma science sponsored by DOE and NSF. BAPSF, and its primary experimental device, the Large Plasma Device (LAPD), provide a platform for studying processes such as plasma waves, collisionless shocks, magnetic reconnection, wave-particle interactions, and turbulence. The Naval Research Laboratory uses the Office of Naval Research (ONR)-sponsored Space Physics Simulation Chamber (SPSC) to complement theory, modeling, and in situ space measurements with laboratory experiments. Often laboratory experiments cannot fully match the relevant parameters and conditions of heliophysics systems. T&M can help connect laboratory experiments with the actual system. SPSC allows for collaborative investigations of space plasma physics under controlled, reproducible, scaled laboratory conditions, suited particularly well to problems addressing the near-Earth space plasma environment. SPSC provides a reasonably realistic testbed facility for the development and preflight testing of space diagnostics and hardware.

In addition to laboratory facilities that explore elements of basic plasma physical phenomena, spectroscopic diagnostics is an important means to determine the physical conditions in solar and heliospheric plasmas. Models of optically thin radiation rely on atomic cross-sections, ionization/recombination rates, electron excitation rates, and radiative decay rates calculated theoretically and validated against laboratory data. Two major resources used for space applications include the CHIANTI atomic database[27] for emission lines for calculating spectra from astrophysical plasmas and the Atomic Data and Analysis Structure (ADAS), which is an interconnected set of computer codes and data collections for modeling the radiative properties of ions and atoms in solar and heliospheric plasmas. However, even though many solar and heliospheric plasmas include very heavy elements, the available databases lack essential data on these elements, and existing codes cannot treat these elements. Benchmarking of atomic data models requires new, high-resolution laboratory spectrometers in the ultraviolet (UV) and X-ray wavelength regions as well as adequate funding for maintaining and updating production codes and databases.

[26] FLARE was constructed by a consortium of five universities (Princeton University; University of California, Berkeley; University of California, Los Angeles; University of Maryland; University of Wisconsin–Madison) and two DOE national laboratories (PPPL and Los Alamos National Laboratory).

[27] "CHIANTI," CHIANTI Database, https://www.chiantidatabase.org, accessed June 2, 2024.

The midterm assessment noted,

> Laboratory research, from plasma physics to spectroscopy, is a critical, foundational component for heliophysics research. The NASA LNAPP [Laboratory Nuclear, Atomic, and Plasma Physics] program is a positive step toward increasing opportunities for laboratory experiments, but it does not fully address the decadal survey recommendation, specifically the need for increased NASA-DOE collaboration. (NASEM 2020, p. 71)

New laboratory measurements of atomic and molecular reaction rates, spectra, cross-sections (collision and ionization, etc.) transition and recombination rates are key to the physical understanding of the ITM system and modeling of this region. Further laboratory measurements of gas–surface interactions are necessary to accurately relate atmospheric density to satellite drag, and thus are important for space weather applications and prediction.

The current facilities developed and used over the past decade do not cover the full range of scales in collisionless regimes mostly targeted by solar and space physics missions. To complement spacecraft observations and numerical simulations, the need for a next-generation laboratory facility is under discussion—for example, the "Solar Wind Machine," which would isolate, control, and diagnose plasma phenomena related to complex solar wind behavior and would have the ability to operate in the collisionless regime and to cover a wider range of scales than the existing laboratory experiments. With costs significantly less than a modern space mission, such a facility could foster, engage, and broaden participation of laboratory and observational space plasma physicists, including space physicists engaged in T&M. A next-generation laboratory facility at the intersection of space physics and basic plasma science may therefore represent an opportunity to respond to the recommendation in *Plasma Science: Enabling Technology, Sustainability, Security, and Exploration* for increased coordination and collaboration by developing a multiagency (NASA, NSF, DOE, ONR, and AFOSR) laboratory-based "space mission" at a fraction of the cost of a real mission (NASEM 2021, p. 377).

5.3.4 Technology Development

Solar and space physics discoveries come from exploring new places as well as from bringing new capabilities to previously visited environments. Advances in technology, particularly those related to new measurement capabilities, are thus critical for advancing science. Improvements in existing instruments (e.g., sensitivity, resolution, reduced accommodation requirements), novel ground-breaking techniques (e.g., imaging of tenuous plasmas), and technologies for multipoint measurements (critical for systems science) are all important directions for making progress on the goals of this decadal survey. A robust and sustained technology development program ensures advancement of measurement capabilities across the full range of maturity, from inception of a novel concept that may or may not work, to mass production of hundreds of instrument copies.

The past decade has seen the rapid emergence of new opportunities that can benefit solar and space physics. These include advances in small satellite technologies, commercial balloons and rockets with rideshare opportunities, and advances in materials science. In 2022, NASA established the Heliophysics Strategic Technology Office (HESTO) to coordinate and manage technology development efforts to carry out the agency's new technology strategy. The new advances and organizational structures provide a solid foundation on which to build a thriving technology program if appropriate investments are put in place.

Instrument Development

Instrument development needs identified for both high-priority science goals of this decadal survey as well as for future missions are shown later in Table 5-8 (Section 5.4.2). Some of these developments can be advanced through current technology programs, while others will require larger investment during specific project formulation phases.

NASA's Heliophysics Technology and Instrument Development for Science (H-TIDeS) Instrument Technology Development program supports development of instrument concepts with a goal of maturing them to the point that they could be proposed for in-flight demonstrations—for example, on rockets, balloons, or CubeSats and eventually on future flight missions. Recognizing that new technology development efforts are not always successful, the recent H-TIDeS solicitations strongly encourage high-risk/high-impact concepts, which the decadal survey committee endorses.

After the potential of new instrument concepts has been demonstrated, opportunities to raise the technology readiness level (TRL, a scale from 1 to 9, with TRL 1–2 being basic technology research, TRL 6—technology demonstration in a relevant environment, and TRL 9—flight proven) are provided by NASA's suborbital and CubeSat programs as well as through technology demonstration options (TDOs) on larger missions. These are described below and in Section 5.4. Results from the TRACE analysis of proposed mission concepts highlighted the healthy technology infusion roadmap of NASA's technology programs, as several prior CubeSat instruments were proposed for the STP and LWS mission concepts. However, the analysis also revealed that some of these instruments may still need significant design modifications and test updates before they qualify for larger-scale, longer-duration science missions with more stressing operational requirements.

The need for multipoint measurements is a theme that emerged from the mission concepts introduced in the community input papers to this decadal survey and were further developed by the panels to address priority science. Many of the mission concepts involve heterogeneous constellations, which comprise several types of measurements made from different vantage points. The implementation of such constellations often involves nonidentical spacecraft and multiple launches. Examples include the prioritized Links notional mission (see Section 5.2) and a host of other concepts that were studied (see Appendixes C, D, and G). Furthermore, building and calibrating the instruments for a large constellation of dozens or more satellites required by some of the concepts requires new processes and capabilities.

The past few years have witnessed an explosion in the number of commercial satellites, many of which are part of mega-constellations for communications (i.e., Internet in space). The increasing number of commercial satellites could mean an increase in opportunities for hosted payloads, providing another means for obtaining multipoint measurements. In a panel discussion hosted by the "Access to Space" working group of this decadal survey, representatives from the commercial sector were unanimously willing to work with the science community to implement hosted scientific payloads onboard commercial spacecraft. However, they also indicated that including hosted payloads is commercially viable only if instruments are hosted on hundreds of their satellites and conform to existing bus resource capabilities. Such resource limitations currently preclude field of view and pointing requirements assumed for many ITM instrument concepts (see Appendix D). Even for instruments with less stringent accommodation requirements, the nonrecurring engineering costs are too high to host only a handful of instruments. The system science goals provide an obvious use case for hundreds of hosted sensors, but the capability to build that many copies of science instruments does not currently exist.

In 2020, NASA established a centrally managed SMD rideshare office to develop standard rideshare processes, provide a single interface between NASA and rideshare providers, and to maximize science return of rideshare opportunities (Mendoza-Hill 2021). This positive step toward improving coordination and identifying rides for heliophysics instruments was taken in response to the report *Agile Responses to Short-Notice Rideshare Opportunities for the NASA Heliophysics Division* (NASEM 2020b) However, the TRACE analysis identified several challenges regarding building multiple high-precision science instruments and pointed out that the limiting factor is the instruments rather than the satellite bus. Building instruments en masse may require instrument technology licensing to multiple providers to enable rapid production through parallel builds. Managing multiple providers requires additional systems engineering and management. Because science instruments are often highly specialized, there may be only a few potential providers, and careful consideration is also needed for science-unique requirements and characteristics such as EMI and magnetic cleanliness, spinning platforms, relatively tight stability and attitude control, or accommodating unique payloads.

The challenges outlined above require concerted efforts to create processes for realizing mega-constellations for science. A HeLEX class of Explorer missions (Recommendation 5-7) could offer opportunities for pathfinder concepts to develop manufacturing processes and capacity for multiple instrument builds that could support even larger constellation missions. A more general discussion of large scientific constellation mission requirements is given in Section 5.4.2.

Conclusion: The multipoint measurements needed to address the science goals of the next decade can be realized by leveraging commercial satellite developments. However, the capability to build many copies of science instruments does not currently exist and represents a major barrier.

Suborbital and CubeSat Platforms

Rockets, balloons, and CubeSats provide valuable scientific data and are an important part of the integrated HSL (Section 5.2). These platforms are also critical for technology development and training of the next generation of scientists and engineers. Because suborbital and CubeSat programs have demonstrated their high value for NASA, the decadal survey committee is concerned about the budget, which has been reduced from $20 million per year to $9 million per year and is held constant at that level in the recent fiscal year (FY) 2025 President's Budget Request (NASA 2024a).

Suborbital flights have long been a testbed for maturing new technologies before they are implemented on expensive spaceflight missions. New sensors and instruments are often deployed on sounding rockets or balloons to gain flight heritage and to improve their performance. Furthermore, suborbital platforms often have extra volume and mass capacity that allows them to accommodate extra "piggyback" instruments. The collection of data in spaceflight conditions has long been an important avenue for testing of new sensor components or complete instruments. For example, the RHESSI detectors were used on balloon-borne investigations for both solar and astrophysics, collecting valuable science data and proving the technology prior to its selection as a SMEX.

NASA SMD now allows scientists to fly their experiments on commercial reusable suborbital platforms such as those provided by Virgin Galactic. The rapid turnaround of such flights enables rapid increase of instrument or subsystem TRL. Because these short suborbital flights can be realized using commercial-off-the-shelf parts, the costs are substantially lower than full space missions. However, it is necessary that NASA coordinates between the companies, who may not be aware of scientists' needs, because the PIs may not have the experience needed for commercial negotiations. A partnership between NASA's Space Technology Mission Directorate (STMD) and SMD can be an effective pathway to supporting PIs and leveraging these opportunities.

The use of small satellites and CubeSats has expanded rapidly over the past decade. As of early 2024, 13 CubeSat missions had launched, and 14 were in development (NASA 2024c). The relatively low cost of the NASA CubeSat program allows for higher risk tolerance making them great platforms for instrument development. As mentioned above, the success of NASA's CubeSat program is demonstrated by the incorporation of CubeSat instruments in the mission concepts proposed in the community input papers to this decadal survey.

Suborbital and CubeSat missions are not only testbeds for technology; they are platforms for gaining mission and leadership experience. These projects provide invaluable training of students and early career researchers in the rigors of spaceflight missions, preparing them for future leadership and hardware responsibility positions. Rocket and balloon missions are ideal training grounds for future PIs of Explorer missions, instrument suites, and other large mission involvement. The skill sets these activities provide include exposure to the NASA mission architecture, team management, complex budget and schedule preparation and management, and leadership experience. In effect, a suborbital program can be a crash course in spaceflight mission design and execution. Future support and expansion of these programs is vital to educating the next generation of instrument providers and leaders for the coming Explorer-class and strategic NASA missions.

As small as they are, CubeSat science missions also need technology advances. In particular, CubeSats need better communications support. It is not uncommon for CubeSats to retrieve only a few percent of the data acquired by their instruments. As communications challenges are a reality for larger missions also, the more risk-tolerant CubeSats provide an opportunity to experiment with novel solutions that could be applied to larger missions (Spence et al. 2022). Other challenges CubeSats encounter include orbital debris requirements, collision avoidance, and radio licensing. Recommendation 5-5 (Section 5.2) encourages NASA and NSF to conduct reviews of their highly valuable and successful CubeSat programs. Recommendation 5-6 urges creation of opportunities for more ambitious and complex CubeSat missions by providing funding in the $10 million to $35 million range, similar to the new Astrophysics Pioneers Program. Building on the earlier success, following these recommendations would allow for even more ambitious CubeSat missions.

NASA Heliophysics Strategic Technology Office

Recently, the Wallops Flight Facility, as part of Goddard Space Flight Center, implemented a new Heliophysics Strategic Technology Office (HESTO) to support NASA's Heliophysics Division in all technology matters. HESTO's tasks include recommendation of strategic investments, management of non-mission-specific technologies within the Heliophysics Division, coordination with other relevant technology groups, and fostering infusion of new technology into future missions.

The implementation of HESTO and its current work on gap and trend analysis and managing of H-TIDeS and HFOS is encouraging. However, the HESTO portfolio is currently limited and includes only a few elements, which are competitively selected through the NASA ROSES solicitation (ROSES B.8 [H-TIDeS] and ROSES B.10 [HFOS]). Current incubating technologies supported by NASA Heliophysics have historically outpaced the available opportunities for demonstration in flight. HESTO is already playing an important role to increase flight opportunities. For example, it works closely with the Sounding Rocket Program[28] and the Scientific Balloon Program[29] to manage flight technology maturation efforts, as well as with the Small Satellite and Special Projects Office that assists SMD with managing small satellite missions.

Conclusion: In addition to current suborbital technology maturation as part of full science investigations, the newly formed HESTO office can play a critical role in matching instrument development teams with technology maturation pathways, ultimately leading to flight demonstration. It would be important for these implementations to evolve into a strong advocate for PIs in negotiating access to space for technology maturation.

Recommendation 5-19: The National Aeronautics and Space Administration (NASA) Heliophysics Division should expand opportunities for instrument development that align with decadal survey goals and provide opportunities for in-flight demonstrations to raise technology readiness levels. NASA should consider expanding the role of the Heliophysics Strategic Technology Office to manage some of these activities and increase collaboration with the Space Technology Mission Directorate as appropriate.

5.4 PREPARATION FOR THE NEXT DECADE AND BEYOND

The decadal survey research strategy provides the framework for making significant progress in each of the focused research areas identified in Chapter 2. The guiding questions within each basic science and space weather theme are broader than these focus areas; continued progress requires a multidecadal effort. Priority areas of investment can be made in the next decade to prepare for future endeavors. These include investments in new technologies and advancing new mission architectures, establishing organizational structures within SMD to enable science that crosses discipline boundaries, and identifying future opportunities for international collaboration.

In May 2021, NASA, NSF, and NOAA sponsored the Heliophysics 2050 workshop to provide a forum for the community to discuss future goals. A second workshop on measurements and techniques was held in February 2022.[30] The vibrant discussions and strong community engagement at these workshops highlighted the importance of planning for the future. Planning for beyond the next decade is an ongoing effort and will require continued engagement by both the scientific community and agencies' leadership.

[28] "Sounding Rockets," NASA, https://www.nasa.gov/mission_pages/sounding-rockets/index.html, updated March 28, 2024.
[29] "Scientific Balloons," NASA, https://www.nasa.gov/scientificballoons, updated January 10, 2024.
[30] "Heliophysics 2050 Workshop," NASA Heliophysics Resources, NASA, https://science.nasa.gov/heliophysics/resources/heliophysics-2050-workshop, accessed June 2, 2024.

5.4.1 Instrument Technology Development

Section 5.3.4 discusses the NASA's Heliophysics research programs that support instrument development and flight opportunities on suborbital and CubeSat platforms that are critical for raising instrument TRLs. Specific instrument technologies requiring further development were identified through this decadal survey's TRACE process (Table 5-8). It should be noted that some of these concepts were not prioritized for the coming decade; all concepts that went through the TRACE process are summarized in Appendix G, and the two prioritized missions are described in Section 5.2.

The prioritized new STP mission concept is a heterogeneous constellation to investigate system-level global coupling between the solar wind, magnetosphere, and ionosphere. Key technology developments needed include the capacity for building multiple copies of the instruments and Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-class spacecraft and maturation of the energetic neutral atom (ENA) narrow angle camera, which is currently at TRL 5. Additionally, the complexity of early operations may require additional ground station resources such as the U.S. Tracking and Data Relay Satellite System (TDRSS) and the Deep Space Network (DSN).

The prioritized new LWS mission concept, a solar polar orbiter (SPO) to explore the solar polar regions, will require developments for boomless magnetometry which is also at TRL 5, and environmental qualification for the compact Doppler magnetograph. Development is in progress for boomless magnetometers on Lunar Gateway HERMES and a 6U CubeSat, but further testing is needed to cover the expected mission environment and the larger, more complex spacecraft. Other needs for an SPO include engineering efforts for deploying Ultraflex solar arrays, addressing thermal and communications constraints, and further trajectory design work to optimize solar pass durations.

In addition to technology needs of the prioritized missions, Table 5-8 captures examples of instrument development needs identified through the TRACE process as potential areas of investment that could enable missions in future decades. A few science use cases are provided below to illustrate the potential benefits of such investments.

Understanding particle acceleration in solar flares has progressed as far as permitted by the technology of the previous decade. The next generation of focusing imaging spectrometers, combined with solid-state detectors capable of detecting individual photons at the high fluxes found in solar flares, and possibly measuring polarization, would allow simultaneous observation of all regions relevant to electron dynamics: acceleration, propagation, and deposition.

The role played by high-energy ions in solar flares is not well understood, even if there are suggestions that the ions may contain a significant share, if not the majority, of the flare energy. Development and deployment of high-resolution (~5 arcsec) imaging gamma-ray spectrometers at energies above 500 keV will pave the way to addressing this question. Another way to measure the ions is by imaging ENAs. Combining observations of the ions with higher-resolution electron observations will resolve the acceleration mechanism and its role in solar flare energetics.

One lingering, crucial challenge in space physics is mapping of magnetic field lines from the equatorial plane to Earth's atmosphere and ionosphere. There are several techniques to approximate this mapping, including use of sophisticated magnetic field models. However, the large uncertainties are apparent when comparing conjunction measurements between equatorial spacecraft and ground-based or low-altitude data. A new method for obtaining definitive mapping of field lines from equatorial regions to their footprints in the ionosphere (Borovsky et al. 2022) uses a particle accelerator onboard an equatorial spacecraft to produce a 1 MeV electron beam aimed into the loss cone. Ground-based all-sky imagers could potentially image the emission of that beam, thus providing the definitive location of the field line footprint. Some development has already been done to advance this concept, and further development to better understand its capabilities could enable its use on future missions.

Understanding the response of the upper atmosphere to solar forcing from above and wave/tidal forcing from below requires a means to measure the temperature, density, and drift of targeted neutral species at thermospheric altitudes. Spatially resolved measurements of neutral temperature, wind, and abundance would untangle the full three-dimensional (3D) structure of the gravity waves (at regional scale) and enable assessment of the energetic state of the entire thermosphere (at planetary scale). These are further discussed in Appendix D. Better characterization of high-order tidal modes, mean flow, and planetary waves would constrain future ITM models at daily

TABLE 5-8 Representative Heliophysics Technologies Identified in the Decadal Survey

Instrument Name	Notional Mission Concept (Domain)	TRL	Instrument Type	Development Needed	Roadmap
Terahertz Limb Sounder (TLS)	BRAVO, I-Circuit, Resolve (ITM)	4/5	Atomic oxygen narrowband heterodyne spectrometer	Low resource (CubeSat compatible) solid state receiver and Schottky diode frequency multiplied local oscillator. Sub 1m class antenna for smallsats. Dual frequency (2.0 and 4.7 THz) capability.	Lab-based sensitivity, power, and thermal performance verification. In space validation on dedicated LEO spacecraft (S/C).
Energetic Neutral Atom (ENA) Imaging	Links (MAG), ion acceleration in solar flares (SH)	5	Time of flight for mass separation, charge conversion of neutral atoms to ions, electrostatic analyzer	Improved angular resolution and sensitivity.	Environmental testing of full prototype.
Boomless Magnetometer	SPO (SH) and other missions (MAG)	5	Magneto-inductive chip-based magnetometer with ML enabled detection	Develop magnetic noise identification methods enabled by ML. Training and baseline noise calibration of ML module with matrixed sensors on notional spacecraft bus.	In space validation on dedicated LEO/highly elliptical orbit smallsat with follow-on accommodation on LWS/STP or Explorer-class mission bus.
Lyman-alpha Hanle Coronagraph	MCEM (SH)	4	Imaging UV spectro-polarimeter	Further system performance modeling to refine design, requirements, and processing. Optical system modified from previous prototypes.	System-level sounding rocket prototype demonstration (intended for 2028).
White Light Coronagraph	SPO and ECH missions (SH) and space weather forecasting	5	Low-level white-light occulting coronagraph with an active pixel sensor	Miniaturized version of STEREO, SOHO.	System-level smallsat or sounding rocket prototype demonstration.
Solar Irradiance Instrument	ECH (SH), thermospheric modeling (ITM), space weather forecasting	5	High dynamic range, short X-ray imager with complementary metal oxide semiconductor (CMOS) detection	Simplified optical design, new Simultaneous High Dynamic Range algorithm with complementary CMOS detectors for compact design.	System-level smallsat or sounding rocket prototype demonstration.
Hard X-ray and Gamma-ray Spectroscopic Imaging Instruments	MCEM	4	Solid state detectors (Ge, CdTe), gamma ray imaging technologies (modulation collimators) and focusing X-ray optics	Adaptation of balloon and rocket experiments to space Mission; hard X-ray optics for 1 arcsec resolution; faster readout electronics.	Further system-level balloon and rocket demonstrations; environmental testing of space instrument prototypes.
Relativistic Electron Accelerator	Referenced by MAG Panel report	4	Active MeV-class modulated electron beam	Radiofrequency cavity design and thermal management, electron injector (gun) design and operation including high-voltage power supply, beam transport design, and ground detection OSSE and architecture optimization.	System-level sounding rocket prototype demonstration.

NOTE: Notional mission concepts referenced are BRAVO (Buoyancy Restoring-force Atmospheric-wave Vertical-propagation Observatory), I-CIRCUIT (Interhemispheric Circuit), SPO (Solar Polar Orbiter), MCEM (Multipoint Comprehensive Eruptive Mission), and ECH (Ecliptic Heliospheric Constellation).

(or better) time variation. Density measurement at orbital altitudes would also significantly improve satellite drag estimates—a key goal for space weather forecasting.

Atomic oxygen (AO) measurements at 2.060 THz and 4.75 THz frequency bands offer an optimal means to gauge thermospheric winds, energy, and dynamics required to address such science and space weather imperatives. These radiofrequency lines are radiometrically brighter (by several orders of magnitude) than visible or near-infrared (IR) AO emission features and can be measured without need for scattered sunlight or auroral correction (Yee et al. 2021). Advances in terahertz local oscillator and heterodyne mixers fabrication, enabled by a series of recent H-TideS grants, have converged to describe the terahertz limb sounder (TLS) as an AO spectrometer capable of providing 4 km limb altitude resolution across 80–400 km altitudes with estimated 5 s integration time per sample (Wu et al. 2016; Wang et al. 2018). The TLS technology development described in Table 5-8 is standard radio frequency engineering required for implementation on a 6U-class CubeSat.

Although the Heliophysics Division research program can support small-scale instrument development, some technology developments will require larger investment and are more appropriately carried out through other programs or as part of mission formulation. NASA currently provides opportunities and incentives for in-space demonstration of heliophysics instrument systems via TDOs on Explorer-class missions. For strategic missions, it may also be possible in some cases to allocate a directed "instrument slot" for use by lower-TRL heliophysics instruments in need of validation.

Conclusion: Advanced instrument technologies will enable scientific discoveries in the decades to come. Heliophysics Division research programs are a critical part of the instrument development pipeline, but larger investments may be required to mature instruments for future flagship missions.

5.4.2 Advancements in Mission Design and Architectures

Advancements in mission design and architectures are also critical for enabling scientific discoveries in the future. These include mega-constellations consisting of tens to hundreds of satellites (or more) and "dipper" missions that can probe deep into Earth's ITM system.

Small satellite technologies and developments in the commercial sector now enable significantly larger constellations than were possible a decade ago. These capabilities are particularly relevant for meeting the systems science needs of Heliophysics (along with Earth sciences). Section 5.3.4 discusses some of the challenges of manufacturing and calibrating the large number of heliophysics science instruments needed for larger constellations. The TRACE analysis of this decadal survey also revealed some other challenges that will need to be solved to realize this new mission architecture.

Before large science constellations can be realized, it is likely that mission assurance guidance and related mission risk class and life cycle cost analysis need to be revised. Currently, the definitions and implementation of risk class focuses on single flight systems or small constellations, not accounting for the fact that larger constellations can permit individual flight elements to have lower mission risk class and yet retain greater constellation resiliency.

Constellation orbit selection impacts the technical effort, cost, and schedule for deployment. Constellations that require satellites to be distributed in orbits with different inclinations or ascending nodes are harder to achieve. Options include multiple launches that increase costs; slow drift, which can impact science mission duration; or onboard propulsion systems that are heavy. Cost savings can be achieved by taking advantage of rideshare opportunities, including to Sun-synchronous and Geosynchronous Transfer Orbit (GTO). However, to take advantage of rideshares, space vehicle design must maintain compatibility with multiple launchers and launch dispensers. Late launch selection for rideshares can increase costs; orbits or launch environments are not well known even late into mission development. NASA has been proactive about engaging with commercial providers. In 2020, the SMD Rideshare Office was established to address these issues.

There are also emerging small launch vehicles that enable launch to unique orbits or the replenishment of constellations. These capabilities need to be explored with launch providers in mission-specific analyses as these vehicles come online.

Increased use of autonomy may be necessary to manage large constellations and their data to reduce ground interactions. Other developing technologies, such as inter-satellite crosslinks, may be needed to ensure data are downlinked with sufficient timeliness or for formation flying to coordinate maneuvers. Use of commercial ground capabilities is likely to be necessary and will require additional coordination and additional ground compatibility testing, as discussed in Section 5.4.4.

Beyond the general considerations above, the TRACE analysis resulted in conclusions specific to heliophysics:

- Many concepts are based on heterogeneous constellations composed of similar, but not identical, spacecraft;
- Maximizing commonality and minimizing nonrecurring engineering can save development costs; and
- These cost savings are best realized with a common vendor; however, this may trade with a longer schedule depending on constellation size.

One surprising result is that common bus designs do not always yield cost savings. A tailored bus solution may be cheaper than an oversized, common bus. Early formulation studies will need to investigate suitable applications for common buses.

The transition region at 100–200 km altitude in the upper atmosphere is a critical but under-explored region of space. This is the region where Earth's atmosphere and the space plasmas interact, and where the electric fields and particle precipitation from above have profound consequences on system dynamics. While the region can be probed by ionospheric radars and other remote-sensing observations, there are very few in situ observations from this region owing to the short orbital lifetimes of spacecraft with perigees at such low altitude. Successful low perigee passes by the Atmospheric Explorer missions brought information on the chemistry and composition, but not of the electrodynamics of the system. A mission with dedicated low-perigee satellites would be ideally suited for exploring this region that has so far been inaccessible.

The mesosphere and lower thermosphere are regions where the dominant driver of the dynamic transitions from the neutrals at lower altitudes to charged particles at higher altitudes. Thus, the dynamics of this region are governed by the combined interacting and coupling of neutral and charged particle populations. Energy transfers between ions and neutrals in either direction, depending on the dominant driving mechanism, and regulates the interaction between the upper atmosphere/ionosphere and the magnetosphere/solar wind. Coordinated multipoint in situ measurements and distributed ground-based observatories will be a gamechanger for understanding this region. To that end, the ESA/NASA Lower Thermosphere–Ionosphere Science (ENLoTIS) working group has explored future lower thermosphere–ionosphere satellite mission concepts. Engineering development work to mitigate effects of the low-perigee environment is expected to be needed. Specifically, the effects of AO on materials, aerothermal heating on ram facing components, and deflection of electric field booms may impact instrument performance and component lifetimes. Additionally, high sensitivity to assumptions used for drag calculation are also a challenge for missions operating at such low altitudes.

5.4.3 Communication Infrastructure Needs for Heliophysics Division

NASA's Space Communications and Navigation (SCaN) Program will provide foundational telecommunication support for space science (heliophysics) missions in the next decade, primarily through its legacy DNS and Near Space Networks (NSN) and emerging commercial networks.

The SCaN program's aspiration to "develop, operate, and manage *all* NASA space communications capabilities" (Volosin 2023) is uniquely challenged by existing HSO missions, which require links over distances from LEO to the outer heliosphere. Likewise, it will be challenging for SCaN to support near-space constellation missions with tens to hundreds of spacecraft, or to support low-latency space weather beacons from instruments on both research and commercial spacecraft.

Of current HSO missions, only a handful are tracked by DSN, and most of those missions are arguably in the near-space range, appropriate for NSN or commercial network support (see Table 5-9). Currently, two operational heliophysics missions—SOHO and PSP—critically depend on the DSN network coverage while accounting for

TABLE 5-9 Range Domain for Heliophysics System Observatory Missions in Operation, Formulation, Implementation, or Study Phase

Domain	Orbit	Range to Earth (km)	Mission	DSN[a]	Near Space[b]
Inner Heliosphere	Parabolic Heliocentric	42–280 × 10^6	Parker Solar Probe		
		25–300 × 10^6	Solar Orbiter		
		10–309 × 10^6	STEREO-B		
	L1 Halo	1.49 × 10^6	SOHO, ACE, WIND		
			CGO, IMAP		
			Mission C[c]		
	L4 Halo	149 × 10^6	Mission C[c]		
Near Moon	Lunar Equatorial	351–415 × 10^3	THEMIS+Artemis		
	Polar Near Rectilinear Halo	~400 × 10^3	HERMES		
Near Earth	High Earth Orbit (HEO)	70.2–382.7 × 10^3	HelioSwarm		
		51.3–190.7 × 10^3	GeoTail		
	Highly Elliptical Earth Orbit (HEEO)	7.00–221 × 10^3	IBEX		
		470–83 × 10^3	THEMIS		
		2.55–153 × 10^3	MMS		
		1.5 × 8 Re 1.3 × 11 Re 1.1 × 15 Re	Mission A[c]		
	Supersynch GEO	36.4 × 10^3	SunRISE		
	Geosynchronous (GEO)	36.1 × 10^3	SDO		
			GOLD		
Low Earth	Sun Synchronous	618 × 658	IRIS		
		671 × 697	Hinode		
		>600	EUVST		
		570	PUNCH		
		504 × 513	AIM		
		~620	MUSE		
	Low Earth Orbit (LEO)	608 × 609	TIMED		
		600	TRACERS		
		413 × 422	AWE (ISS)		
		590	EZIE		
		TBD	GDC		
		TBD	DYNAMIC		
		600	Mission B[c]		
Outer Heliosphere	Mars Surface	56–401 × 10^6	RAD (MSL)		
	Mars Orbit	56–401 × 10^6	ESCAPADE, MAVEN		
	Jupiter Orbit	5.9–9.7 × 10^8	Europa Clipper		
Interstellar	Hyperbolic Heliocentric	23.8 × 10^9	Voyager 1		
		19.9 × 10^9	Voyager 2		

[a] Current (blue) and future (orange) HSO missions listed on the September 2023 DSN dashboard provide an example of DSN usage at a snapshot in time.
[b] Near space boundary defined by range to Earth <2 × 106 km—green shading.
[c] Notional Missions A. B and C, studied by current decadal survey, are included for reference (Table 5-10).
NOTE: CGO, Carruthers Geocorona Observatory; ISS, International Space Station; MAVEN, Mars Atmosphere and Volatile Evolution; MSL, Mars Science Laboratory; RAD, Radiation Assessment Detector.

more than 20 percent of DSN antenna utilization hours during FY 2022 (NASA 2023a). Meanwhile, the DSN and NSN system capacity must also contend with planetary, astrophysics, Earth sciences, and international space missions.

System-wide telecommunications pressure comes at a time when many DSN and NSN assets are aging, new heliophysics sensors are generating rapidly increasing data rates, and the lunar exploration (Artemis) program is levying strict requirements for contiguous network coverage for safe crewed operations. A recent investigation of DSN congestion pointed out a significant loss of science coverage while assets were focused on the Artemis-1 mission primary spacecraft and associated rideshare SmallSats (Foust 2023).

NASA has proactively responded to this looming communication crisis on multiple fronts, including increasing the total number of 34 m DSN antennas, enhancing half of those antennas for high-capacity Ka-band operation, creating a new subnetwork of 17 m antennas solely for Lunar Exploration Ground Support, and exploring how commercial network partners can offload network demand. NASA SCaN actively pursues international partnerships to provide additional large apertures with increased geographic coverage. NASA is also exploring the role of infrared laser communications in increasing system capacity and has recently reported high-definition television-class data rates from a deep space lasercom system at a range of 16 million km (roughly 0.1 AU) (NASA 2023b).

The notional space science mission concepts created for this decadal survey included assessing the optimal use of the heterogeneous NASA network (DSN, NSN, and commercial partners). Table 5-10 lists the concepts that set the highest demands for the network in terms of data downlink rate, number of spacecraft, range to Earth, and orbit architecture.

During the Artemis-1 mission, the communication resources required by Exploration System Development Mission Directorate (ESDMD) missions have tended to get priority over SMD science missions. Recognizing that such conflicts have occurred before, the Space Operations Mission Directorate (SOMD), SMD, and ESDMD carried out the “DSN Futures Study,” which seeks to address near-term network issues (network scheduling efficiency, network and element brittleness, and fragility), and projected capability needs through 2050. Furthermore, NASA SCaN has discussed creation of a joint “prioritization working group” between the same invested parties to better prepare for and mediate mission conflicts. For this prioritization working group to fairly gauge all future missions, it is critical to evaluate the full set of U.S. government, international, and commercial communication obligations outside of NASA.

Conclusion: Increasing pressure on NASA’s shared communications infrastructure has the potential to create significant conflict, impacting future Heliophysics missions. A NASA-wide study is needed to find solutions before the situation becomes untenable.

TABLE 5-10 “Most Stressing” Notional Mission Concepts

ID	Mission Type	Orbit Configuration	Number of Spacecraft	Max Rate
A	Magnetospheric Constellation	$1.5 \times 8\ R_E$	8	9.2 kbps
	(HEEO 24 S/C)	$1.3 \times 11\ R_E$	8	7.6 kbps
		$1.1 \times 15\ R_E$	8	8.2 kbps
B	Thermospheric Constellation	600 km polar inclination	72	2.0 kbps
	(LEO 72 S/C)	6 planes, 30 spacing		
		12 S/C per plane		
C	Inner Heliophysics Constellation	Sun–Earth L1 Halo	2	250 Mbps
		Sun–Earth L4 Halo	1	42 Mbps

5.4.4 Cross-Divisional and Cross-Directorate Coordination at NASA

Transformational research is often found at the boundaries between disciplines, and both cross-agency and cross-divisional collaboration have proven to be highly productive (Section 5.3). While cross-agency collabora-tion will remain important in future decades, this section focuses on cross-divisional coordination within NASA. Some of the most pressing and fundamental questions are shared across science divisions at NASA, and the unique expertise and skills of scientists from across SMD need to be harnessed to forge new frontiers. The solar and space physics community has developed a detailed expertise in understanding how a star interacts with its planets and is eager to share that knowledge in partnership with other divisions.

Cross-divisional research is discussed in Section 5.3.3, but collaboration needs to begin with the missions that provide data to enable scientific breakthroughs. There is a long history of collaboration between the Heliophysics and Planetary Sciences Divisions. The solar and space physics community has made major contributions to the scientific discoveries of interdisciplinary missions (see Section 2.3), starting from the Voyagers traversing the heliosphere (with groundbreaking observations in the magnetospheres of Jupiter, Saturn, Uranus, and Neptune along the way) to planetary missions such as MESSENGER at Mercury, MAVEN at Mars, Galileo and Juno at Jupiter, and the Cassini mission to Saturn. More recently, PSP made flybys of Venus, fueling the debate about the assumption that the magnetic field of Earth protects the planet from atmospheric escape (Figure 5-18).[31]

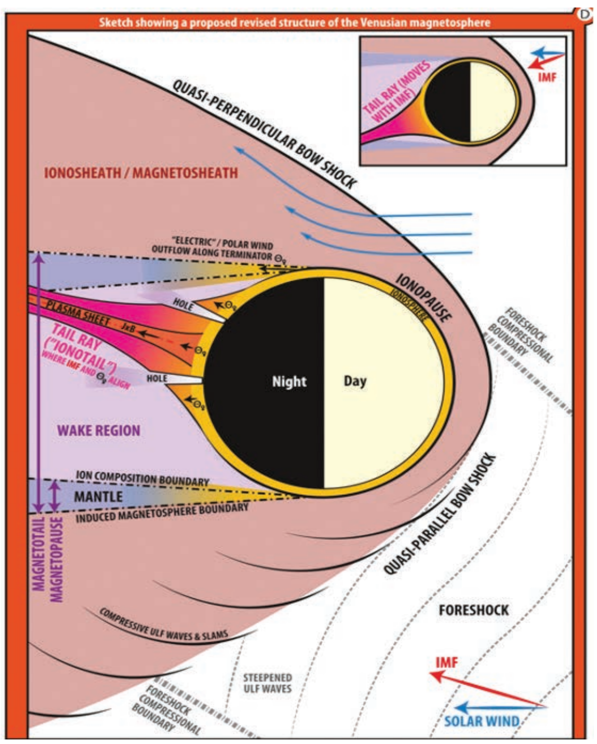

FIGURE 5-18 Parker Solar Probe Venus flyby provided new insights into planetary magnetospheres.
SOURCE: Collinson, et al., "A Revised Understanding of the Structure of the Venusian Magnetotail from a High-Altitude Intercept with a Tail Ray by Parker Solar Probe," John Wiley and Sons. Collinson, G.A., Ramstad, R., Frahm, R., Wilson, L. III, Xu, S., Whittlesey, P., et al., 2021, "A Revised Understanding of the Structure of the Venusian Magnetotail from a High-Altitude Intercept with a Tail Ray by Parker Solar Probe," *Geophysical Research Letters* 48:e2021GL096485, https://doi.org/10.1029/2021GL096485.

[31] "Parker Solar Probe Captures Its First Images of Venus' Surface in Visible Light, Confirmed," NASA, https://www.nasa.gov/general/parker-solar-probe-captures-its-first-images-of-venus-surface-in-visible-light-confirmed, updated July 26, 2023.

Such opportunities enable quantitative comparisons of the solar wind interactions with the atmospheres of Earth, Venus, and Mars, critical for advancing understanding of planetary magnetospheres.

Opportunities exist for capitalizing on both the traditional mechanism whereby one division participates in another division's mission (e.g., smaller missions that are achievable within a certain division's budget but could be augmented to do more science by collaboration), and for truly cross-divisional missions (and funded by SMD) where scientists from each division are involved from the planning stages through the whole mission.

An example of a smaller mission is MAVEN where a Planetary Discovery mission included substantial Heliophysics objectives on the solar wind interaction with Mars's atmosphere and ionosphere. For much earlier missions—Voyager, Galileo, Cassini, and MESSENGER—space physics goals were included in the original science objectives and highly capable (for the time) particles and fields instruments were competed and selected. In more recent years, as planetary missions have developed more specific and demanding science goals (requiring more payloads), the particles and fields instrumentation has become more limited (e.g., JUICE, Europa Clipper). Nevertheless, NASA and ESA are to be commended for setting up working groups to support interplanetary science on the cruise phases of JUICE and Europa Clipper as well as coordinating observations upstream and within the magnetosphere of Jupiter.

Looking to future missions, ESCAPADE (Escape and Plasma Acceleration and Dynamics Explorers) is a Mars mission funded by Heliophysics (originally selected in the Planetary SIMPLEx program) that is due to launch in 2024 to send two spacecraft to study solar wind energy and momentum through Mars's unique hybrid magnetosphere. At Jupiter, the measurements of the intense radiation belts by Juno generated enthusiasm in Earth's radiation belt community about a future mission to Jupiter that would send multiple spacecraft orbiting within the planet's intense radiation belts to quantify particle acceleration, transport, and loss processes. Owing to the strength of Jupiter's intrinsic magnetic field and the presence of Io, the radiation belt environment is extremely different from Earth's. Yet some similar related phenomena have been observed, such as aurora, ultra-low-frequency and chorus waves, and solar wind–driven storms. Such a mission would be primarily for space physics but with some planetary applications and would be important for understanding particle acceleration processes.

The scientific overlap between Earth science and solar and space physics has garnered more interest in recent years. Changes in concentrations of anthropogenic greenhouse gases CO_2, and also CH_4 and H_2O, have caused warming in the troposphere, as well as cooling in Earth's stratosphere and ITM system. For example, decreasing trends in thermospheric mass density of ~1 to ~10 percent per decade depending on altitude has been inferred from aerodynamic drag of LEO satellites. These decreasing trends in air mass density have significant implications on space debris accumulation. Owing to these significant and persistent anthropogenic trends, there is a need to understand ITM climate change and its impact in support of improved prediction and potential mitigation efforts. Particle precipitation can cause chemical changes in the mesosphere and lower thermosphere that can then propagate to lower altitudes and affect the concentration of ozone in the stratosphere. This is primarily observed in the polar winter and is a result of the polar vortex strength and other dynamics that are not fully understood. When and where the effect of energetic particle deposition is most significant is also not well known. This coupling between the magnetosphere and ionosphere–thermosphere system is of great interest to climate scientists, especially if it can explain some of the under-estimated chemical effects found in whole atmosphere model runs (e.g., Randall et al. 2005). Studies of these effects do not fit neatly into either Earth science or the solar and space physics funding opportunities, thus, it would be of great benefit to explicitly provide opportunities for cross-divisional research between ESD and HPD.

Some missions are truly cross-divisional and may require significant investment well beyond any single division's budget. For example, the Habitable Worlds Observatory (with origins in the 2020 astronomy and astrophysics decadal survey [NASEM 2023]) has a broad scope of exploring habitability of exoplanets and would benefit from involvement of solar and space scientists (as well as planetary and Earth scientists). Similarly, a mission to interstellar space would be an ambitious multidecade mission to send a spacecraft out of the heliosphere to 1000 AU, deep in the very local interstellar medium (VLISM). This would be a truly cross-divisional mission with Heliophysics, Planetary and Astrophysics objectives that need to be addressed by an interdisciplinary team. Such a mission will take time to develop, including technologies such as "next generation" radioisotope thermoelectric generator power systems, enhanced communications, and, perhaps, onboard data processing.

Space weather is another critical area of cross-divisional coordination at NASA. It is broadly recognized that radiation prevention and prediction are important to include in planning of Moon-to-Mars missions. Space situational awareness is not only important for commercial space but is impacting NASA missions. The expertise of solar and space physicists can contribute to the nation's most pressing needs in these areas.

Advances in technology are also critical. Measurements at 0.2 AU would increase the lead time by a factor of 20, reaching about 10- to 20-hour lead time that would substantially enhance the ability of space weather users to take protective action (NASEM 2022). While there are other implementations, solar sails are one propulsion technology that could enable this. Solar sail technologies are being developed that would allow placing a solar wind monitor at 1.8 times the distance to L1 (approximately 0.02 AU), which would almost double the lead time from the present 40–60 minutes, and with L1 monitors, would allow monitoring the changes in the arriving interplanetary coronal mass ejection structure (e.g., Akhavan-Tafti 2023). The technology still requires flight demonstration.[32]

Conclusion: A cross-divisional approach is needed in planning, operation and management of projects and programs to address interdisciplinary science issues in the near- and long term.

Recommendation 5-20: The National Aeronautics and Space Administration Science Mission Directorate (SMD) should develop a cross-divisional approach for planning, operation, and management of future projects and programs for interdisciplinary science. Specifically,

- **Include science representatives from all SMD divisions in the planning stages for Habitable Worlds Observatory;**
- **Support development of a mission to interstellar space and other future, large, long-term cross-divisional missions;**
- **Coordinate inclusion of interdisciplinary instruments on flagship missions to diversify science opportunities (e.g., include particles and fields instruments on Uranus Orbiter Probe, support for Europa Clipper cruise phase);**
- **Facilitate the cross-divisional aspects of space weather (e.g., radiation prevention and prediction) in particular, in the planning of Moon-to-Mars missions;**
- **Proactively engage with the Space Operations Mission Directorate (SOMD) and the Exploration Systems Development Mission Directorate (ESDMD) to ensure that communications needs for SMD missions will continue to be met in the future;**
- **Assess science-enabling instrument and flight system technology needs for the next generation, including next-generation radioisotope thermoelectric generators and solar sails.**

5.4.5 Future Opportunities for International Coordination

Solar and space physics is an interdisciplinary and global undertaking whose success relies on strong international collaboration. As pointed out earlier, the scientific value of such collaboration has been recognized and strongly encouraged by previous solar and space physics decadal surveys, and NSF, NASA, and NOAA are to be applauded for their wide-ranging engagement with the international community. Looking forward, this section highlights specific opportunities for coordination with international partners.

NSF currently supports U.S. partnerships in incoherent scatter radars (AMISRs, Jicamarca) and worldwide networks such as SuperDARN and GONG. It also enables the aggregation and dissemination of data from a ground-based networks such as SuperMAG, a network of magnetometers distributed around the globe, or a Global Neutron Monitor Network. NSF international engagement extends to 20 nations located in the Americas, Asia, Europe, and Africa.

NASA is deeply engaged with the international community through active missions such as Hinode, IRIS, PSP, Solar Orbiter, WIND, SOHO, STEREO, MMS, and THEMIS. It is also collaborating with the international

[32] This paragraph was updated after release of the report to reflect the status of solar sail propulsion technology.

community through confirmed missions like NASA's IMAP mission (expected to be launched in 2025), ESA's Vigil mission (to be launched around 2031), and Japan Aerospace Exploration Agency's (JAXA's) Solar-C mission (to be launched around 2028). The THEMIS mission is supported by a Canadian ground-based network of all-sky imagers. NASA supports launch sites at a variety of locales for both sounding rockets (e.g., Norway and Sweden) and balloons (e.g., New Zealand, Australia, Sweden, and Antarctica). NASA has cultivated partnerships with sister space agencies such as ESA and JAXA, observatories, and institutes. As discussed in Section 5.2.3, international collaborations are in progress in the area of space weather through SWFO and Space Weather Next programs.[33]

Ongoing and expanding opportunities for international collaboration are key to the success of the decadal strategy outlined herein, to address the core science program and to support space weather science and operations. On the ground, there is increased need for measurements around the globe with heterogeneous instrument arrays—for example, the DASHI concept. In space, opportunities may be available for international participation in the upcoming program of record GDC and DYNAMIC missions as well as in the recommended notional LWS SPO and STP Links missions. In this context, it is noted that ESA's Voyage 2050 Senior Committee Report specifically describes the scope for international cooperation in the areas of solar polar science and magnetospheric constellations (ESA 2021). Such cooperation would share costs and thus enable more rapid development of these missions. Planning future missions involving two or more space agencies may benefit from coordinated community effort such as that represented by the ENLoTIS international working group. The decadal survey committee notes that on July 22, 2024, this working group issued a report on the scientific case for a satellite mission to the lower thermosphere–ionosphere transition region, which represents the first steps toward potential ESA-NASA cooperation on developing such a mission (ESA/NASA 2024).

Last, an area of international collaboration that promises large science return on a modest monetary investment is to leverage the active international coordination between existing ground- and space-based instruments to jointly address scientific objectives. This can be achieved by, for example, coordinating multiobservatory campaigns, sharing consolidated data sets with the international community for scientific analysis, and by supporting the development of tools for coordinated data analysis. So far, these efforts have been largely voluntary with limited resources available at the institutional or agency level. The development of tools to enable coordinated observations, coordinated data analysis, and data sharing between international partners would facilitate such collaborations (see Recommendation 5-1).

5.5 REFERENCES

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[33] This paragraph was modified after release of the report to accurately reflect which country supports the network of all-sky imagers.

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6

Summary of Research Strategy and Budget Implications

6.1 INTRODUCTION

Chapter 5 introduced the decadal survey committee's strategy to advance the solar and space physics enterprise—one that is ambitious, but realistic; comprehensive in scope; and balanced to afford the most effective implementation. When implemented in its entirety, this research strategy supports the two major thrusts for solar and space physics:

- *Explore our habitable cosmos:* Exploring the space around us to gain a view of the only known habitable system in the universe.
- *In the service of humanity:* Analyzing the space environment to project its future changes.

With this two-pronged approach, the strategy makes significant progress on the wide-ranging science themes described in Chapter 2, the space weather themes described in Chapter 3, and the development of a robust solar and space physics community as described in Chapter 4.

The research strategy is certainly ambitious to mirror the ambitious science and space weather guiding questions in Chapters 2 and 3. For the National Aeronautics and Space Administration (NASA), the strategy completes the highest-ranked Living With a Star (LWS) and Solar Terrestrial Probes (STP) missions from the previous solar and space physics decadal survey, *Solar and Space Physics: A Science for a Technological Society* (NRC 2013; hereafter "the 2013 decadal survey") and adds two new and transformative missions that obtain the first images of the Sun's polar regions and combine in situ and remote sensing of the tenuous plasmas in Earth's space environment. For the National Oceanic and Atmospheric Administration (NOAA), the strategy envisions significant growth in its space weather programs. For the National Science Foundation (NSF), the recommended program grows to include three new ground-based projects.

The research strategy is also realistic. The technology exists or requires minimal investment for the recommended missions and projects in the next decade. DRIVE+ includes enhancements to the Diversify, Realize, Integrate, Venture, Educate (DRIVE) initiative introduced in the 2013 decadal survey, building on the significant achievements in the previous decade. If sufficient resources are provided, then the entire research strategy can be accomplished in the next decade.

Significant challenges in realizing this research strategy are the budget and budget profile for the agencies. At NASA, the budget for the Heliophysics Division and the projected budget profile are insufficient to implement what the committee considers to be an essential research strategy. In fact, the budget and projected profile are insufficient to complete the missions recommended in the 2013 decadal survey as well as those that are currently in development.

Over the previous decade, delays in the development of the high-priority Geospace Dynamics Constellation (GDC) and Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC) missions were owing to the combination of insufficient budgets and the application of "decision rules" that favored the expansion of the Explorer program over strategic missions. Mission delays, coupled with the increased selection rate for Small Explorer (SMEX) and Medium-Class Explorer (MIDEX) missions in the two Explorer program opportunities in 2016 and 2021, have resulted in significant financial pressure on the NASA Heliophysics Division budget for the next decade. Despite this budget pressure and previous budget history, the Heliophysics Division component of this research strategy is realistic and achievable, but only if budget increases commensurate with its ambitions are secured. Such growth will enable significant progress toward ground-breaking scientific exploration and essential space weather contributions to society.

Highlights of the recommended program for the Heliophysics Division and their mapping to report recommendations are shown below. These highlights are in the order they appear in Chapters 3, 4, and 5, and additional details are found in these chapters.

- A Space Weather Program whose growth over the decade is sufficient to complete the space weather instrumentation currently in development and to fly a SMEX-class space weather demonstration mission. (See Recommendation 3-5 in Chapter 3 and the discussion in Section 5.2.)
- Growth in the basic research budget to maintain a robust research and analysis (R&A) program through healthy proposal success rates, implementation of a new Pioneers-like program, a study to ensure the continued success of the CubeSat program, and a new "mission-class" theory and modeling program. (See Recommendations 5-4, 5-5, and 5-6 in Section 5.2 and Recommendation 5-16 in Section 5.3.)
- A vibrant Explorer program that maintains a 3-year cadence for Explorer opportunities, has Mission of Opportunity (MO) calls for each Explorer opportunity, and has a new, proposed Heliophysics Large Explorer (HeLEX)-class mission with the first opportunity late in the decade. (See Recommendation 5-7 in Section 5.2.)
- Successful completion of all elements the program of record that are in development, with the simultaneous launch of GDC and DYNAMIC in 2031 to complete and implement the remaining high-priority 2013 decadal survey recommendations. (See Recommendation 6-1 in this chapter.)
- A new, constellation-class STP mission that has both remote and in situ observations that result in a comprehensive understanding of the flow of mass and energy through the complex magnetosphere–ionosphere system. (See Recommendation 5-8 in Section 5.2.)
- A new LWS mission that explores the Sun's polar regions, the last unexplored region of the solar atmosphere and interior. (See Recommendation 5-9 in Section 5.2.)

The budget implications for highlights of the recommended program for the Heliophysics Division are shown in Table 6-1. The recommendations are grouped by their chapter and section in the order they appear in this report (and thus are not listed in priority order). The agency or agencies responsible for implementation are listed in the second column and the third column provides an estimate of the total budget increase (summed over fiscal year [FY] 2025 through FY 2034) above the FY 2024 President's Budget Request (NASA 2023) in real-year dollars (RY$). Entries in Table 6-1, including all state of the profession topics, are listed with a not applicable (N/A) total budget increase. The lack of a budget impact is not an indication of their lack of importance. In most cases, including many of the state of the profession entries and the cyberinfrastructure modernization entry, the budget impact is extremely difficult to quantify beyond the general understanding that, for any given entry, it is in the millions of dollars. All recommendations, including those with no specified budget impact, are summarized in Table 6-3 at the end of this chapter.

TABLE 6-1 Budget Implications for the Recommendations in the Comprehensive Research Strategy

Recommendation Topic	Agency	Total Budget Increase (Real Year Dollars [RY$])	Cross-Reference (Recommendation Number)
Space Weather			
Establish a space weather research program	NOAA	$125 million	3-4
Grow the Space Weather Program to support space weather enhancement missions	NASA	$191 million	3-5
Consider hosted space weather demonstration payloads for all missions	NASA	$1 million–$30 million per payload[a]	3-6
State of the Profession			
Fund demographic data collection	NASA, NSF, NOAA	N/A	4-1
Expand definition of broader and broadening impacts	NASA, NSF	N/A	4-2
Faculty Development in geoSpace Sciences (FDSS)	NSF	N/A	4-3
Expanding the reach of space science in education	All	N/A	4-4
Enhancing DEIA+	All	N/A	4-5
Increase public outreach and citizen science programs	All	N/A	4-6
Integrated HelioSystems Laboratory (HSL)			
HSL coordination	All	N/A	5-1
Mid-scale Research Infrastructure (MSRI)	NSF	$4 million–$20 million MSRI-1 $20 million–$100 million MSRI-2	5-2
Major Research Equipment and Facilities Construction (MREFC)	NSF	$238 million[b]	5-3
Flagship-level Community Science Modeling Program	NASA	$125 million	5-4
CubeSat programs	NASA, NSF	$122 million	5-5
Fill the suborbital to Mission of Opportunity cost and risk gap	NASA	$91 million	5-6
NASA Explorer missions	NASA	$75 million[c]	5-7
Solar-Terrestrial Probes mission	NASA	$1.58 billion[d]	5-8
Living With a Star mission	NASA	$1.03 billion[e]	5-9
DRIVE+			
Continue to support development of modern cyberinfrastructure	NSF, NASA	N/A	5-11
Augmentation of Heliophysics Division research program	NASA	$193 million	5-16
Expand opportunities for instrument development; expand the role of the Heliophysics Strategic Technology Office	NASA	$57 million	5-19

TABLE 6-1 Continued

Recommendation Topic	Agency	Total Budget Increase (Real Year Dollars [RY$])	Cross-Reference (Recommendation Number)
Preparations for Beyond the Decade			
Cross-divisional approach for future projects and programs	NASA	N/A	5-20

NOTE: N/A = budget increase is assumed to be small (<$10 million) or negligible compared to total FY 2024 budget.

[a] Notional budget not included in the NASA Heliophysics Division budget profile in Figure 6-1.

[b] Estimated cost in FY 2023 dollars.

[c] Total difference between a Heliophysics Large Explorer (HeLEX) mission in 2031 and a Medium-Class Explorer (MIDEX) mission in 2031 for FY 2031–FY 2034. For FY 2035–FY 2040, $510 million total difference between a HeLEX mission in 2031 and a MIDEX mission in 2031.

[d] $1.58 billion development costs in FY 2027–FY 2034, $118 million development costs for FY 2035, and $175 million operations costs for FY 2036–FY 2039 for a total mission cost (Phases A–E) of $1.86 billion.

[e] $1.03 billion development costs in FY 2029–FY 2034, $575 million development costs for FY 2035–FY 2036, and $476 million operations costs for FY 2037–FY 2049 for a total mission cost (Phases A–E) of $2.08 billion.

6.2 BUDGET ANALYSIS

6.2.1 National Science Foundation

From the many compelling potential investments in critical ground-based infrastructure, the committee identifies three (one for each program) and suggests the appropriate funding vehicles for each, as follows (see Recommendations 5-2 and 5-3 in Section 5.2):

- *Mid-scale Research Infrastructure (MSRI)-1:* The observing system simulation experiment (OSSE) study of the Distributed Array of Scientific Heterogeneous Instruments (DASHI);
- *MSRI-2:* Implementation of the Frequency-Agile Solar Radiotelescope (FASR); and
- *Major Research Equipment and Facilities Construction (MREFC):* Development of the Next Generation Global Oscillations Network Group (ngGONG).

The committee notes that additional budgetary growth may be needed to accommodate a revitalization of the CubeSat program (see Recommendation 5-5 in Section 5.2). In addition, an agencywide strategy and adequate funding are needed to support NSF's increasing space weather responsibilities under the 2020 Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT Act; P.L. 116-181) (see Recommendation 3-1 in Chapter 3). Details on the budget required to support this growth are outside this decadal survey's scope.

6.2.2 National Oceanic and Atmospheric Administration

Similarly, the NOAA budget must grow to accommodate the increased integration of NOAA space weather assets into space weather research (see Recommendation 3-4 in Chapter 3) and to accommodate the extensive and ambitious program of space-based and ground-based space weather assets in the next decade. However, the committee did not perform an analysis of the required budget growth, because it was outside this decadal survey's scope. Costs for the creation of a space weather research program (see Table 6-1) were assumed to be the same as those for the NASA flagship-level community science modeling program.

6.2.3 U.S. Air Force

Increased support will be needed to accommodate the space weather roles prescribed for the Department of Defense (DoD)/U.S. Air Force in the PROSWIFT Act. However, the committee did not perform an analysis of the required budget growth as it was outside this decadal survey's scope.

6.2.4 NASA

Figure 6-1 shows the fiscal year costs of the major elements of the NASA Heliophysics Division budget for the FY 2025 to FY 2034 period covered in this decadal survey. The profile is presented in RY$, adjusted for inflation using the New Start Inflation Index for FY 2023 as the basis for the year-over-year inflation calculations from FY 2025 through FY 2032 (the inflation indices for FY 2033 and FY 2034 were assumed to be the same as that for FY 2032). All budget estimates are categorized, to the extent possible, to be consistent with the Heliophysics Division 2024 President's Budget Request. Costs that do not directly result from recommendations in the "Comprehensive Research Strategy" (Chapter 5), such as support for the Wallops Flight Facility and program management overhead, are taken directly from the FY 2024 Budget Request, which is assumed to remain level after FY 2028 and then inflated appropriately to RY$.

At its current level, the Heliophysics Division budget is not sufficient for implementation of the comprehensive research strategy proposed in this decadal survey, which was developed to accomplish the most important science identified for the next decade. In the budget growth recommendations below, a RY$ budget

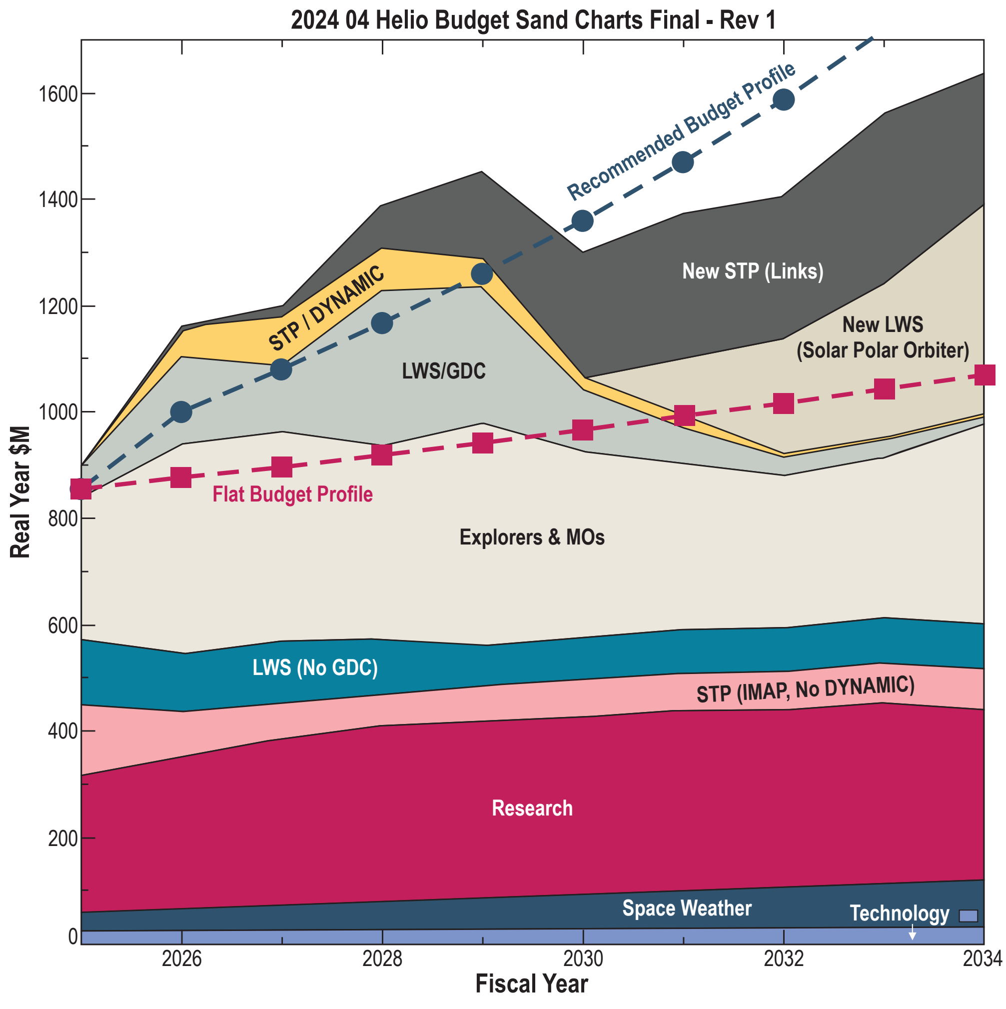

FIGURE 6-1 NASA Heliophysics Division budget profile for the next decade. Elements of this budget reflect approximately the fiscal year (FY) 2024 President's Budget Request. The full NASA contribution to the comprehensive research strategy is realized with an increase in the overall division budget (blue dashed line) that occurs in two steps: a 17 percent increase in FY 2026 and 8.5 percent growth.
SOURCE: Composed by AJ Galaviz III, Southwest Research Institute.

of $856 million is assumed for FY 2025. This FY 2025 budget is consistent with the budget profile for FY 2024 and FY 2025 in the FY 2024 budget request. Growth occurs in two stages from this FY 2025 baseline: a one-time increase followed by reasonably steady growth over the remainder of the decade. The recommended budget profile in Figure 6-1 reflects this two-stage growth. The sum of this profile over the 10 years of the next decade is equal to the total budget needed for the Heliophysics Division. The budget in any given year is not necessarily consistent with this recommended profile because the precise phasing of programs is the responsibility of the Heliophysics Division.

This two-stage budget growth represents the investment that is crucially needed in solar and space physics science and space weather research. With this budget profile, NASA will have the means to implement its part of the comprehensive research strategy (see recommendations in Sections 5.2 and 5.3). Below, the augmented elements of the research strategy are discussed along with their budget implications, as summarized in Table 6-2. The full budget profile is shown in Figure 6-1.

Conclusion: To complete the program of record, to resume GDC in 2026, and to put GDC and DYNAMIC on schedule to launch in 2031, NASA's Heliophysics Division budget needs to increase by approximately 17 percent from FY 2025 to FY 2026 to $1 billion. To fully implement the decadal survey's comprehensive research strategy after this initial FY 2026 budget increase, the Heliophysics Division budget needs to grow by approximately 8.25 percent each year to the end of the decade.

Technology

Technology program investments are vital for the future of the Heliophysics Division, both in the next decade and beyond. This budget is taken directly from the FY 2024 President's Budget Request and is augmented by $5 million per year in FY 2024 dollars. This additional investment is notional and directed toward the Heliophysics Strategic Technology Office (HESTO) office; it provides a solid foundation to build a thriving technology program.

Research

Research is fundamental to advancing NASA heliophysics science. The research budget, as defined in the FY 2024 President's Budget Request includes mission and research support, data management, operations of some of the Heliophysics System Observatory (HSO) infrastructure space missions (e.g., Voyager and Wind), the suborbital and CubeSat programs, and the Heliophysics Guest Investigator (HGI), Heliophysics Supporting Research (HSR), and most other grants solicited under the Research Opportunities in Space and Earth Science (ROSES) solicitation. Additional research funding is included in the LWS Science and Heliophysics Technology programs.

In FY 2025, research accounts for about 30 percent of the budget. The research strategy assumes funding for these research elements per the FY 2024 President's Budget Request with level funding for some elements. For example, level funding through the next decade is assumed for most HSO science and infrastructure missions, with the exception of missions nearing the end of their lifetime. For example, Voyager operations are funded through 2030, per the latest NASA estimate for the end of the mission. Funding augmentations for several elements are described below and summarized in Table 6-3 at the end of this chapter.

The Heliophysics CubeSat program is at $9 million for FY 2025, which is less than half of the maximum funding level during the previous decade. In Section 5.2, there is a recommendation for a review of the NSF and NASA CubeSat programs to ensure that their success over the past decade continues (Recommendation 5-5). In the Heliophysics budget for the next decade (Figure 6-1), funding for the CubeSat program is assumed in FY 2025 to return to $20 million/year and to grow with inflation thereafter. The actual funding level for this important science and training program would be determined in the recommended review.

Recommendation 5-16 in Section 5.3 requests that the Heliophysics Division maintain a success rate of at least 25 percent for ROSES research proposals without decreasing the average size of the research grants. Accomplishing such success rates requires a budget increase for the HGI and other R&A program elements. While the exact increases need to be determined yearly, a representative increase of 20 percent for most

TABLE 6-2 NASA Heliophysics Division Assets

Element	Heliophysics Division Asset
Technology, research, suborbital and CubeSats, and community modeling	Heliophysics technology
	Research programs, including NASA CubeSats and the NASA suborbital program
	NASA flagship-level community modeling program
Other space-based program development	NASA Space Weather Program
	NASA Heliophysics Explorers
	NASA Solar Terrestrial Probe (STP) mission line management, Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC), and new STP mission
	NASA Living With a Star (LWS) mission line management, Geospace Dynamics Constellation, and new LWS mission

NOTE: All of these assets have implications for the NASA budget and are discussed in this section.

Heliophysics Division research programs is assumed in FY 2026, and the new budget is assumed to grow with inflation thereafter.

Recommendation 5-4 introduces the flagship-level community science modeling program. This significant community endeavor is envisioned to be at a level similar to that of an Explorer MO. Per the recommendation, the actual cost and phasing is still to be determined. Indicative of the envisioned effort, the NASA research budget is augmented by $125 million in RY$ and this funding is spread over a 5-year development phase starting in FY 2027 followed by a 2-year operations phase at lower funding.

NASA Space Weather Program

The Space Weather Program grows each year from its baseline FY 2025 budget of $36 million such that its annual budget doubles by the end of the decade, as depicted in Figure 6-1. This baseline budget includes Space Weather Centers of Excellence, which are similar in scope to the DRIVE Science Centers, as well as other research and analysis associated with research to operations. The baseline budget also includes two hosted payloads: the Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES) instrument suite on the Gateway space station and the solar imaging instrument on the European Space Agency Vigil mission. These payloads represent the beginning of a space weather demonstration line implemented as hosted payloads, funded from and managed by the Space Weather Program. Furthermore, additional hosted demonstration payloads not yet planned are assumed to be funded from this baseline budget. The number and total cost of these hosted payloads are not known; however, the assumed cost of an individual payload is in Table 6-1.

In addition to the Space Weather Program baseline budget, there is an additional budget increase of approximately $190 million in RY$ over the next decade. This increase funds a new line of stand-alone space weather technology demonstration missions (Recommendation 3-5). The allocated funding is sufficient for a mission up to the size of a SMEX but is not sufficient for a standalone launch (according to the current Explorer budget guidelines). Therefore, other options such as a rideshares need to be pursued. Beyond the next decade and funding permitting, this program might grow to include a MIDEX-class space weather demonstration mission line.

NASA Heliophysics Explorers

The Explorer program has been extremely successful over the past decade with several missions launched and operating. However, this success has come at a price. In the FY 2024 President's Budget Request, the Explorer

TABLE 6-3 Recommendation Topics, Agencies, and Cross-Referenced Sections for the Comprehensive Research Strategy

Recommendation Topic	Agency	Cross-Reference (Section)
Space Weather		
3-1 Foundation-wide strategic space weather plan	NSF	3.3.1
3-2 Space weather user surveys to set priority research goals	NOAA, AFOSR[a]	3.3.2
3-3 Space weather research targeted to prioritized goals	NASA, NSF	3.3.3
3-4 Space weather research program and predictive models	NOAA, AFOSR	3.3.4
3-5 Space Weather Program growth to support space weather demonstration missions	NASA	3.3.5
3-6 Space weather mission enhancements	NASA	3.3.5
3-7 New data streams for operational services	NOAA	3.3.5
State of the Profession		
4-1 Fund demographic data collection	NASA, NSF, NOAA	4.2.1
4-2 Expand definition of broader and broadening impacts	NASA, NSF	4.3.1
4-3 Faculty Development in geoSpace Sciences (FDSS)	NSF	4.3.2
4-4 Expanding the reach of space science in education	All	4.3.2
4-5 Enhancing DEIA+	All	4.4.2
4-6 Increase public outreach and citizen science programs	All	4.5.2
Integrated HelioSystems Laboratory		
5-1 Manage all assets as part of an integrated HelioSystems Laboratory	NASA, NSF, NOAA	5.2.1
5-2 Mid-scale Research Infrastructure (MSRI)	NSF	5.2.2
5-3 Major Research Equipment and Facilities Construction (MREFC)	NSF	5.2.2
5-4 Flagship-level Community Science Modeling Program	NASA	5.2.2
5-5 Review of CubeSat programs	NASA, NSF	5.2.3
5-6 Suborbital to Mission of Opportunity cost and risk gap	NASA	5.2.3
5-7 Heliophysics Explorer missions	NASA	5.2.3
5-8 Solar-Terrestrial Probes Program	NASA	5.2.3
5-9 Living With a Star Program	NASA	5.2.3
DRIVE+		
5-10 Research that combines ground- and space-based observations	NASA, NSF	5.3.2
5-11 Cyberinfrastructure development	NASA, NSF, NOAA, AFOSR	5.3.2
5-12 Cross-disciplinary research	NASA, NSF	5.3.2
5-13 NSF organizational structure review	NSF	5.3.2
5-14 Funding for infrastructure missions to validate data	NASA	5.3.3
5-15 Support for analysis of archival data	NASA	5.3.3
5-16 Augmentation of Heliophysics Research Program	NASA	5.3.3
5-17 Theory and modeling for strategic missions	NASA	5.3.3
5-18 Review the structure of DRIVE Science Centers and Space Weather Centers of Excellence	NASA	5.3.3
5-19 Instrument development	NASA	5.3.4
Preparations for Beyond the Decade		
5-20 Cross-divisional approach for future projects and programs	NASA	5.4.4
Decision Rules		
6-1 Decision rules for the recommended program	NASA	6.2.4

[a] The Air Force Office of Scientific Research (AFOSR) is a sponsor of the decadal survey; the Department of Defense (DoD) would determine if it is the appropriate entity to implement the recommendation.

program constitutes 44 percent of the Heliophysics budget by FY 2026. The Explorer program comprises several elements, including management; Explorers and MOs in development, in prime operations, and in extended operations; and future Explorers and MOs. The funding for management and extended operations is assumed to be that of the FY 2024 President's Budget Request. Management and extended operations of existing Explorers is approximately 15 percent of the total Explorer program budget for FY 2025, and these elements increase to 21 percent of the total budget in FY 2026 under the assumption that all missions continue extended operations. Beyond FY 2027, these two elements are assumed to have a nearly flat budget (in FY 2024 dollars), with modest increases to account for the addition of those Explorers and MOs that reach extended mission operations.

The Explorer budget from the FY 2024 President's Budget Request includes completion of the Explorers and MOs currently in development. These include two MIDEX missions selected in February 2022 that are in early development. The HelioSwarm mission budget follows the FY 2024 President's Budget Request profile and an estimated life-cycle cost of $550 million through prime mission (FY 2030). Similarly, the Multi-slit Solar Explorer (MUSE) budget follows the FY 2024 President's Budget Request profile with an estimated life-cycle cost of $350 million through prime mission (FY 2029). Both mission life-cycle costs include access to space. However, because these missions have not yet been confirmed, a baseline cost commitment has not been determined. Any growth in these costs will negatively impact the budget and result in further delays for new heliophysics science.

Recommendation 5-7 (Section 5.2) discusses the cadence of the Explorer program and introduces a new HeLEX-class explorer. The budget implications for these recommendations are discussed below.

A single mission downselect is assumed from the SMEX FY 2022 announcement of opportunity (AO), with Phase A currently in progress and Phase B is assumed to start in FY 2025.[1] The budget profiles used for all Explorers are based on an estimate provided by NASA. These budgets were in FY 2022 dollars and have been inflated to RY$ per the NASA inflation index. The total life-cycle cost assumes project development at the cost cap and includes the cost of program management and access to space. As an example, the SMEX selected in 2022 has a life-cycle cost of $329 million in FY 2022 dollars.

The Explorer budget includes a MIDEX AO and a MO AO released in FY 2025 with downselect and project start in FY 2027. While it is recommended that the MIDEX and MO AOs be separated, the budget profile assumes that the two AOs are released in the same year. Note that offsetting the two AOs has a very minor impact on the overall budget. The principal investigator (PI) cost cap for the FY 2025 MIDEX solicitation (not including access to space) is assumed to be $300 million in FY 2024 dollars to account for increased program costs. The budget uses the funding profile provided by NASA's Heliophysics Division, subsequently inflated to RY$ to match the solicitation profile. The MIDEX Phase B development starts in FY 2028. The cost cap for FY 2025 MO is $70 million using the profile provided by NASA.

Following Recommendation 5-7, the budget includes a HeLEX mission AO in 2031 at a PI cost cap of $600 million in FY 2022 dollars with downselect/project start in 2033. Funding and phasing are scaled from doubling the MIDEX FY 2022 PI cost cap (including access to space). When inflated to RY$, this project results in ~$150 million burden in the next decade and ~$1.1 billion from FY 2033 through FY 2040. For the next decade, the budget increase in Table 6-1 is calculated by determining the difference in costs for selecting a HeLEX instead of a MIDEX in 2031. This follows from assuming that MIDEX and HeLEX will be solicited in an alternating fashion, always with a SMEX in between.

Increasing the cadence of the Explorer program was a high priority for the 2013 decadal survey. The increase was largely successful; the next decade will see an Explorer or MO launch every year. However, the result of the rapidly increased cadence is that large sums are held in reserve for launch vehicle costs, and the share of the total budget spent on Explorers and MOs has increased dramatically. Adding the selection of two MIDEX missions in FY 2022, the Explorer program will comprise 44 percent of the total budget in FY 2026

[1] For NASA missions, the life cycle of a project is defined as a series of phases. Pre-Phase A: Concept Studies; Phase A: Concept and Technology Development; Phase B: Preliminary Design and Technology Completion; Phase C: Final Design and Fabrication; Phase D: System Assembly, Integration and Test, Launch; Phase E: Operations and Sustainment; and Phase F: Extended Mission Operations and Closeout. NASA References, "SEH 3.0 NASA Program/Project Life Cycle," NASA Headquarters, https://www.nasa.gov/reference/3-0-nasa-program-project-life-cycle, updated July 23, 2023.

and approximately the same percentage in FY 2027. This growth puts significant pressure on the rest of the Heliophysics Division budget.

A vibrant and strong Explorer program can extend into the next decade and relieve pressure on the Heliophysics Division budget by maintaining a 2- to 3-year cadence. In the budget profile in Figure 6-1, the decrease in the Explorer and MO budget starting in FY 2030 is the result of resolving the backlog and assuming only single selections for new Explorers starting with the FY 2022 SMEX. Additional savings could potentially come from engaging the Venture Class Acquisition of Dedicated and Rideshare (VADR) launch services to help reduce access to space costs.

Solar Terrestrial Probes Mission Line Management, Dynamical Neutral Atmosphere–Ionosphere Coupling, and the New Solar Terrestrial Probes Mission

The STP and LWS mission lines are both essential to the scientific discoveries discussed in Chapter 2. The STP management funding includes the STP missions in development, funding to complete development, launch, prime and extended mission operations for the Interstellar Mapping and Acceleration Probe (IMAP), and extended mission funding for other STP missions in the HSO. All elements of the STP missions are funded at a level that matches the FY 2024 President's Budget Request. The IMAP budget assumes launch in FY 2025, prime mission through FY 2027, and extended mission beyond FY 2027. Funding for the Magnetospheric Multiscale Mission (MMS), Solar Terrestrial Relations Observatory (STEREO), Hinode, and Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) extended missions is also included, assuming they all continue operations with funding at the levels of the FY 2026 budget in later years.

The budget profile for DYNAMIC development is shown separately as it is not included in the FY 2024 President's Budget Request. DYNAMIC development cost and phasing (including management and excluding access to space) was provided by NASA. The total life-cycle cost is $335 million, and the phasing of the development is designed to ensure that this important mission launches within ±3 months of GDC in FY 2031 to allow for coordinated operations.

The highest-priority new STP mission for the next decade is a constellation mission similar to the notional Links Between Regions and Scales in Geospace, or "Links" mission. A summary of the technical and cost information obtained from the technical, risk, and cost evaluation (TRACE) process is in Appendix G. The Links concept is a flagship-class system science mission concept that illuminates the dynamic connections of the near-Earth space environment. It is an ambitious heterogenous constellation-class mission with 24 in situ spacecraft and two imaging spacecraft. Consistent with the TRACE analysis, a 7-year development is assumed with a new start in FY 2027 (before the launch of DYNAMIC) and launch no earlier than FY 2035. The total estimated life-cycle cost of this mission is $1.86 billion of which $117 million of development and operations costs would impact beyond the next decade. This total cost includes a space weather enhancement as suggested in the Panel on Space Weather and Science Applications report in Appendix E and assessed by the TRACE analysis (see Appendix G).

Living With a Star Mission Line Management, Geospace Dynamics Constellation, and the New Living With a Star Mission

The LWS mission line is the strategic mission line that focuses on basic science discoveries that may have implications for space weather. The management funding includes all items shown in the FY 2024 President's Budget Request maintained at their projected levels. These items include Solar Orbiter collaboration, LWS science, program management, and extended operations for Solar Dynamics Observatory (SDO) and Parker Solar Probe (PSP).

Because GDC is not included in the FY 2024 President's Budget Request, its budget profile is shown separately in Figure 6-1. This budget profile was provided by NASA and follows the recommendations of the Independent Review Board (IRB) report (NASA 2022) with full development restart in FY 2025 and launch in FY 2031 together with DYNAMIC. The total estimated life-cycle cost is $1.2 billion through the prime mission.

The highest-priority new LWS mission for the next decade is the notional Solar Polar Orbiter (SPO), a mission focusing on the Sun's polar regions. A summary of the technical and cost information obtained from the TRACE process is in Appendix G. SPO is a bold mission to image the Sun from a completely new vantage point to answer fundamental questions about the generation of the solar magnetic fields, and determine how those fields drive solar activity and shape the heliosphere. The mission uses planetary gravity assists to achieve a 3-year orbit that is >70 degrees out of the ecliptic, allowing extended periods of observation of both the northern and southern polar regions of the Sun. The mission lifetime spans at least one solar activity cycle. A new start for this mission is planned for FY 2029 as GDC development is ramping down. Phase B starts in 2031, after the GDC launch, and a 6-year development was included for this deep space mission development that includes Jupiter and Venus gravity assists. The mission has a total life-cycle cost of ~$2.08 billion, of which approximately half is realized before FY 2034, assuming launch in FY 2037. The prime mission operations extend over a solar cycle to FY 2049.

Budget Growth and Decision Rules

The program budget assumes an increase in FY 2026 and then annual budget growth of approximately 8.5 percent for the remainder of the next decade. This budget growth is needed to implement the research strategy and to make significant progress on the priority science in Chapter 2 and in NASA's contribution to space weather (see Chapter 3).

If the Heliophysics Division budget remains flat at FY 2024 levels, then almost all science focus areas in Chapter 2 will be seriously compromised. In this flat budget scenario, none of the augmentations will be implemented, nor will any flagship mission be completed in the next decade. That is, GDC and DYNAMIC, high priorities from the 2013 decadal survey, would not be completed, and there would be no new STP or LWS missions in the next decade. They delay of these missions would seriously compromise the HSL. A flat budget would result in an unprecedented situation where funding would be insufficient to complete even the highest-priority STP and LWS missions from the 2013 decadal survey. The failure to complete GDC and DYNAMIC would seriously upset the balance of the recommended strategy because these two missions are the only ones that provide substantial progress on the ionosphere–thermosphere–mesosphere components of science focus areas in Chapter 2. Furthermore, STP and LWS missions, with their expanded resources, advance science in several focus areas, whereas the smaller Explorer missions cannot realistically meet the challenges of the broad guiding questions in Chapter 2. A flat budget would be devastating to the entire solar and space physics community. The field would shrink as researchers and engineers would have no incentive to enter or remain, knowing that there are neither exciting scientific opportunities nor funding to support their efforts.

A flat Heliophysics Division budget could be highly damaging to society. The proliferation of low Earth orbit (LEO) satellites to meet the increasing demand for communication and location services increases the likelihood of collisions with potentially catastrophic consequences and greatly exacerbates space traffic management challenges (Boley and Byers 2021). The spacecraft operators need improved characterization of orbital environments, including drag and orbital debris impacts. Adequate monitoring and prediction of the radiation environment are also essential to enable humans and their technological systems to venture again beyond the protection of LEO. Indeed, an unprotected astronaut working on the lunar surface will depend on adequate warning systems for their survival.[2]

Power grids are already challenged by the variable loads introduced as renewable energy sources are integrated with conventional fossil fuel energy sources. Space weather–induced disturbances could be devastating to networks that already operate close to their limit capacity. A detailed understanding and ability to forecast the impact of magnetic storms is needed now, to inform the development of the 21st century power grid, which needs to handle these highly variable loads.

These concerns have been acknowledged in recent legislation, such as the PROSWIFT Act, which aims to improve monitoring and prediction of the space environment. These improvements will only be possible with a better understanding of the underlying processes. In short, the space weather goals in Chapter 3 cannot be accom-

[2] See Smith and Scalo (2007) and references therein, which notes that "The August 1972 [solar particle event] SPE, often taken as the standard high-fluence event for protection studies, was not an isolated anomaly. The February 1956, November 1960, October 1989, and October–November 2003 events produced solar particle fluxes sufficiently large that an astronaut on the moon protected by only a spacesuit would likely have perished, and many events approaching these fluences have been recorded."

plished with a flat budget. In particular, the failure to launch GDC and DYNAMIC seriously compromises the outcome for atmospheric driving in the first space weather theme (System of Systems: Drivers of Space Weather; see Section 3.2.1) and will result in a dearth of observations in LEO that are essential for ionospheric space weather modeling (see Section 3.3.5). A decade-long pause in advancement of solar and space physics, combined with a loss of talent, has potentially catastrophic implications, because other pursuits rely on this knowledge and workforce.

Building on the accomplishments already made by the program of record, the research strategy maximizes the exciting and rewarding science for the next decade while maintaining and enhancing space weather research programs, including pathways from research to operations. To be successful, the strategy will leverage all elements of the program of record, including GDC and DYNAMIC, and will require sustained budget growth over the decade. If this sustained budget growth is insufficient to accomplish the entire research strategy, then decision rules must be implemented.

Recommendation 6-1: If there is insufficient funding to accomplish the entire research strategy, then NASA should implement decision rules in the following order:

- **First, delay the start of the Living With a Star (LWS) Solar Polar Orbiter reference mission; and then**
- **Delay the start of the Solar Terrestrial Probes (STP) Links reference mission;**
- **Delay the Space Weather budget augmentation for space weather demonstration missions;**
- **Delay the announcement of opportunity for the next Explorer/Mission of Opportunity (but revert to the 3-year cadence after budget conditions become favorable again);**
- **Delay implementation of the community science modeling program;**
- **Delay the augmentation of the Heliophysics Research Program;**
- **Delay the development, implementation, or launch of the Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC) STP mission; then**
- **Delay the development, implementation, or launch of the Geospace Dynamics Constellation (GDC) LWS mission.**

For the Explorer program, if there is a delay in this important program, its 2- to 3-year cadence would resume once funding is available. With their associated delays, the invocation of even some of these decision rules will significantly impact the solar and space physics community and society. In the decadal survey committee's view, a failure to capitalize on the opportunities presented in this report would result in a true "lost decade" for solar and space physics.

The decision rules are designed to preserve the completion of the program of record at the expense of everything that would be new for the next decade, even the augmentation of the Heliophysics Research Program. The rules are also designed to have the largest impact later in the decade, under the assumption that the budget challenges will compound as the decade progresses. Last, the decision rules respond to budget shortfalls and are listed in the order they should be implemented. As additional funding becomes available, they should be implemented in reverse order.

Significant cost increases for the LWS and STP missions, including those in development, would have a disproportionate effect on the overall budget profile and program balance. While any strategic mission called out in this report is an integral part of the committee's balanced strategy, none should be allowed to jeopardize the entire portfolio. Therefore, if any LWS or STP mission life-cycle costs increase more than approximately 30 percent over the estimated cost at Key Decision Point-B (KDP-B),[3] the committee suggests that NASA conduct a standard continuation review of the program and implement the changes that come out of that review. However, it is important for such reviews to consider the implications for program balance across the entire program. For example, if the GDC mission costs increase by 30 percent over its estimated life-cycle costs at KDP-B, a review of the program's future would include consideration of the mission's relation to other elements of the Heliophysics Division flight program.

[3] KDP-B is the key decision point where a NASA project transitions from concept and technology development to preliminary design and technology completion. KDP-C is the key decision point where a NASA project transitions from Preliminary Design and technology completion to final design and fabrication. This KDP is also called confirmation.

With balance across mission size, cadence, and sub-discipline, as well as the size of the associated organizations, the research strategy encompasses all solar and space physics. With full community support, this balanced strategy is attainable. It also leverages the enormous public success of the Heliophysics Big Year (Guhathakurta 2023), which included the Great American Eclipse of 2024, an event that could be witnessed by 12.2 million Americans living in the path of totality and tens of millions more living within the shadow of the penumbra. The largest coronal mass ejection event in 20 years also brought space weather into public view, with possibly one of the strongest displays of auroras on record in the past 500 years (NASA 2024).

The research strategy includes a robust program of LWS and STP missions slated for development over the next decade. Additionally, the Explorer program can leverage rapidly advancing technologies to conduct targeted scientific research and address crucial gaps not covered by the LWS and STP missions. Optimizing all the elements of the research strategy and with full community support, the next decade will become the golden age of discovery and understanding of our local cosmos and humanity's place in it.

6.3 REFERENCES

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Appendixes

A

Statement of Task

The National Academies of Sciences, Engineering, and Medicine shall establish a Decadal Survey Committee (the "Survey Committee") to develop a comprehensive science and mission strategy for solar and space physics (heliophysics) research and operations with recommended activities for a 10-year period beginning in approximately 2024. The Survey Committee—informed by the activities of National Academies–appointed study panels, informal working groups, and input from the solar and space physics community—will generate consensus recommendations to advance and expand the frontiers of solar and space physics in the current decade and lay the groundwork for continued advances in future decades.

The report from the Survey Committee will:

1. Provide an overview of the current state of solar and space physics science and applications, including:
    a. Topics historically part of solar and space physics decadal surveys, including:
        i. The structure of the Sun and the properties of its outer layers in their static and active states,
        ii. The characteristics and physics of the interplanetary medium from the surface of the Sun to interstellar space beyond the boundary of the heliosphere, and
        iii. The consequences of solar variability on the atmospheres and surfaces of other bodies in the solar system, and the physics associated with the magnetospheres, ionospheres, thermospheres, mesospheres, and upper atmospheres of Earth and other solar system bodies;
    b. New and emerging frontiers where solar and space physics expertise enables significant advances, including but not limited to:
        i. Science related to the interstellar medium, astrospheres (including their stars), exoplanets, and planetary habitability, and
        ii. Applications related to robotic and human exploration in and beyond low-Earth orbit and the lunar environment; and
    c. The space weather pipeline from basic research to applications to operations, including the research-to-operations-to-research loop that strengthens forecasting and other predictive capabilities.

2. Describe the highest-priority science goals to be addressed in the period of the survey. In doing so:

   a. Identify the focused parts of those goals where measurable progress can be made, where frontiers can be expanded, and that improve possibilities for scientific growth in the future; and
   b. Note where an interdisciplinary or system science approach is needed.

3. Develop a comprehensive ranked research strategy that provides an ambitious, but realistic, approach to address these science goals. The strategy will include consideration of:

   a. The combination of ground- and space-based investigations to enhance progress on the prioritized science goals.
   b. Data and computing infrastructure needed to support the research strategy and the long-term utility, usability, and accessibility of acquired data;
   c. Technical, risk, and cost assessments of recommended major investments, when deemed useful;
   d. Decision rules that can accommodate reasonable projected budget deviations or changes in activities' urgency; and
   e. The international landscape, interagency collaborations, public–private relationships, and innovative partnerships.

4. Assess the state of the profession, encompassing, but not limited to:

   a. Identifying the workforce expertise and capabilities needed to implement the scientific and technical priorities identified by the survey, including the identification of paths for entry into the community, needs for professional development, and challenges to workforce retention;
   b. Evaluating the health and vitality of the community working in the solar and space physics subfields, which includes:

      i. Assessing, to the greatest extent possible, the subfields against the metrics for health and vitality established by the Foundation for Assessing the Health and Vitality of the National Aeronautics and Space Administration (NASA) Science Mission Directorate's Research Communities [study report due to be published Q1 2022], and
      ii. Identifying challenges to the community responding to new and emerging scientific fields;

   c. Identifying issues of concern regarding diversity, equity, accessibility, and inclusion; and
   d. Recommend, using established best practices, actions to improve the health and vitality of the community.

Recommendations regarding operational space weather activities and/or projects shall be directed to only the National Oceanic and Atmospheric Administration (NOAA). Recommendations regarding establishing new or supporting established ground-based observatories shall be directed to only NOAA and the National Science Foundation, as appropriate. Recommendations regarding spaceflight projects shall be directed to only NOAA and NASA.

B

Report of the Panel on the Physics of the Sun and Heliosphere

Solar and heliospheric physics covers a vast domain, extending from the core of the Sun to the boundary between the heliosphere and interstellar space. This field aims to understand how the Sun generates energy, how it powers the solar dynamo that creates and sustains a complex and highly variable magnetic field, and how it forms and upholds the heliosphere, the farthest reaches of the Sun's atmosphere. It seeks to unravel what drives solar activity, how the solar wind is formed and evolves on its journey from the corona to the heliopause (HP), and how the heliosphere interacts with the interstellar medium.

There are important practical aspects to this field. The heliosphere is humanity's home in the galaxy, and the dynamic interactions it contains have consequences for a society that is reliant on space-based and ground-based technologies impacted by the sudden and violent energy releases occurring throughout the space environment. Understanding these interactions is essential for protecting life on Earth and for safeguarding humanity as it expands to the Moon, Mars, and beyond.

B.1 STATE OF THE FIELD

The previous decade has seen many new discoveries and considerable advances in the basic understanding of solar and heliospheric physics. Tasked with identifying the highest-priority science goals (PSGs) related to the Sun, the heliosphere, the very local interstellar medium, and pertinent emerging interdisciplinary opportunities, the Panel on the Physics of the Sun and Heliosphere (SHP) considered the wealth of significant accomplishments from the past decade to guide the next. Here, the panel lists several of these achievements, organized by the overarching PSGs (not in prioritized order)—that will guide solar and heliospheric science in the coming years. Each section lists several key new discoveries as well as important science questions that have arisen from these and other recent revelations.

B.1.1 How Does the Sun Maintain Its Magnetic Activity Globally from Pole to Pole?

The previous decade included a much weaker sunspot cycle, with a considerably lower mean sunspot number, than the two that preceded it. This followed a period of very weak solar activity and a long, deep sunspot minimum. The solar wind flux and magnetic field were considerably weaker during the previous solar minimum, while the flux of galactic cosmic rays reached the highest on record. New discoveries continue to be made from operational missions within the Heliophysics Systems Observatory (HSO) and solar ground-based facilities—now including the Daniel K. Inouye Solar Telescope, the most advanced solar telescope in the world. The past decade has also seen great progress in solar dynamo modeling, which has always been a challenging problem because the dynamo is inherently a multi-spatial-scale system. The "mean field model," capturing physics of small scales via parametrizations, and full three-dimensional (3D) models, targeting explicit dynamics over a wider range of scales, are gradually converging toward a unified understanding of the dynamo that will likely come to fruition in the next decade when the physics of polar regions will be addressed.

Highlights of additional major science advancements from the past decade include the following:

- *Numerical modeling of the solar dynamo:* 3D global magnetohydrodynamic (MHD) simulations are now producing results that are relevant to the solar case, including the reversal of the solar field polarity (toroidal field reversals) and key aspects of the well-known butterfly diagram. Mean field models now well represent important aspects of the dynamo process such as magnetic buoyancy, nonlinear "quenching" of turbulent diffusion, and kinetic helicity, which result in realistic torsional oscillation patterns seen in helioseismology observations.
- *Helioseismic measurements of solar rotation and meridional circulation:* A major advancement of helioseismology has been the accurate measurement of solar rotation as a function of both latitude and radius in the convection zone, tachocline, and interior. While helioseismic techniques cannot measure magnetic fields directly, recent observational advances in solar rotation and meridional flow measurements have shown that the fields' amplitudes and variations are clearly influencing velocity dynamics, allowing us to probe the structure and strength of subsurface solar magnetic fields.
- *Discovery of Rossby waves:* One of the major, unanticipated discoveries of the past decade is the detection of Rossby waves in the Sun (Figure B-1). These inertial waves, first detected in Earth's atmosphere, occur in thin spherical shells owing to the latitude variation of the Coriolis forces. Terrestrial Rossby waves interact with the mean zonal flow to produce "jet streams" that steer the daily weather. Analogously, solar Rossby waves can interact with solar differential rotation and toroidal magnetic fields to affect the distribution of active regions and enhance bursts of solar activity.

Some of the key questions remaining in this field include the following: Does the meridional flow go all the way to the pole or do counter-cells occur? At what latitude do the polar fields reverse? What is the nature of polar vortices? What is the temperature difference between the poles and the equator? This topic will be explored further in Section B.2.1.

B.1.2 How Do the Sun's Magnetic Fields and Radiation Environments Connect Throughout the Heliosphere?

The past decade has seen a significant increase in the understanding of the physics of the solar chromosphere, corona, and solar wind. Parker Solar Probe (PSP) was launched in 2018 and has markedly advanced the understanding of how the solar magnetic field is connected with the inner heliosphere. The seamless coverage of spectral diagnostics from the photosphere into the low corona—by the Interface Region Imaging Spectrograph (IRIS) satellite and a host of complementary, high-resolution, ground- and space-instruments—now allows researchers to precisely investigate the connectivity between solar surface drivers and phenomena observed in the upper atmosphere. This effort is supported by increasingly sophisticated numerical models of the solar atmosphere that now include critical nonequilibrium effects such as time-dependent ionization and ion-neutral interactions, which greatly affect the structure of the chromosphere and transition region (TR). Some of these models are starting to reproduce quintessential chromospheric features such as spicules or fibrils.

Highlights of additional major science advancements from the past decade include the following:

- *First advances in understanding the slow solar wind:* Periodic density and magnetic structures are commonly observed in the slow solar wind, indicating a source related to intermittent plasma release associated with

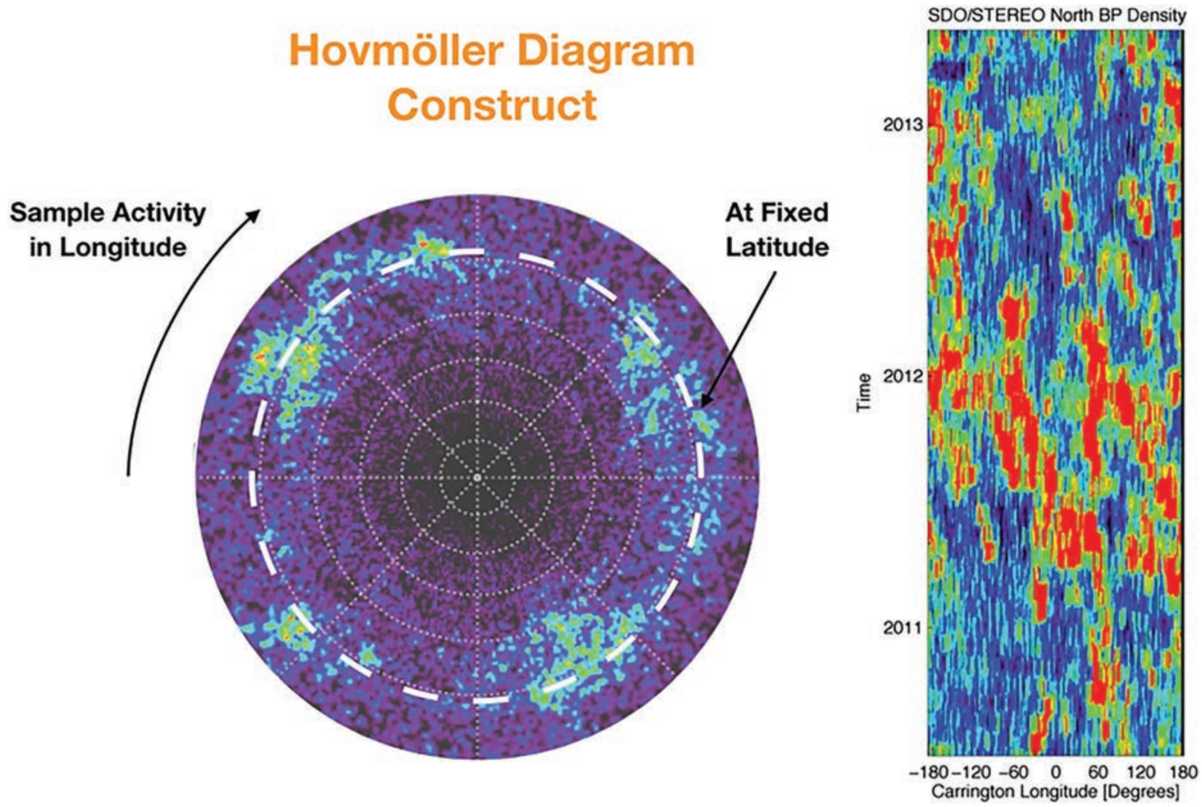

FIGURE B-1 (*Left*) A combined Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly and Solar Terrestrial Relations Observatory (STEREO)/Extreme UltraViolet Imager (EUVI) extreme ultraviolet bright point (BP) density image for December 2011. From a time series of such images, a Hovmöller diagram can be constructed by sampling the longitudinal evolution of the BP density in a narrow range of latitudes over time. (*Right*) The annuli are then stacked to represent the passage of time. In this example, the evolution of the BP density is shown and was the original case used to diagnose the presence of Rossby waves in the global-scale magnetic flux systems of the solar interior.
SOURCE: Dikpati and McIntosh (2020), https://doi.org/10.1029/2018SW002109. CC BY 4.0.

interchange reconnection. Pseudostreamers are a prime location for interchange reconnection, with observed structure size scales that are consistent with those found in the periodic structures. Models of the solar coronal magnetic field driven by photospheric flows show ubiquitous interchange reconnection along coronal hole boundaries between open and closed fields, which is likely the dominant process capable of explaining key observations of the slow solar wind, including more variability, and enhanced ionic and elemental composition.

- *Proving the existence of nonthermal particles in coronal nano-flares:* It has long been thought that quiescent active regions are heated primarily by so-called nanoflares, episodes of small-scale magnetic reconnection leading to nonthermal accelerated particles and impulsive heating of the coronal plasma, but there has been no direct proof. IRIS ultraviolet (UV) spectroscopy of the chromospheric and TR response to small, rapid coronal heating events has revealed that for a large fraction of them the observed velocity pattern can be explained only by a population of coronal nonthermal electrons, dissipating their energy in the lower atmosphere. This pattern has been confirmed by highly sensitive hard X-ray (HXR) observations with the Nuclear Spectroscopic Telescope Array (NuSTAR) astrophysics satellite, which have unambiguously proven the presence of nonthermal accelerated particles in small-scale events.

- *Discovery of a highly structured solar wind magnetic field near the Sun and magnetic "switchbacks":* PSP observed complex magnetic structure in the solar wind, including the existence of "magnetic switchbacks" (Figure B-2). Beyond a few solar radii, the interplanetary magnetic field (IMF) was expected to be nearly radial; however, PSP found it to contain numerous structures in which the field reverses direction. Researchers have connected the timing of the occurrence of switchbacks to variations in the solar wind velocity and have identified their solar source, providing strong evidence that interchange reconnection is the likely origin of the fast solar wind.
- *Measuring the magnetic wave origin of First Ionization Potential (FIP) bias in active regions:* Exciting results, obtained by combining coronal spectroscopy and first observations of chromospheric magnetic field temporal variations, have recently demonstrated a likely origin of the "FIP bias" (the overabundance of elements with low FIP as measured in coronal plasma). Its spatial distribution observationally links to sites of strong Alfvénic perturbations in the chromosphere, providing strong evidence that the fractionation process producing the FIP bias is powered by the conversion of magnetic waves in the chromosphere.

Some of the key questions remaining in this field include the following: How does the lack of far-side and polar observations of the Sun impact the ability to accurately describe global solar wind, coronal mass ejection (CME), and energetic particle propagation? What role do interchange reconnection and waves and turbulence play in generating the solar wind, and how do they imprint on the fast and slow solar wind? What is the role of

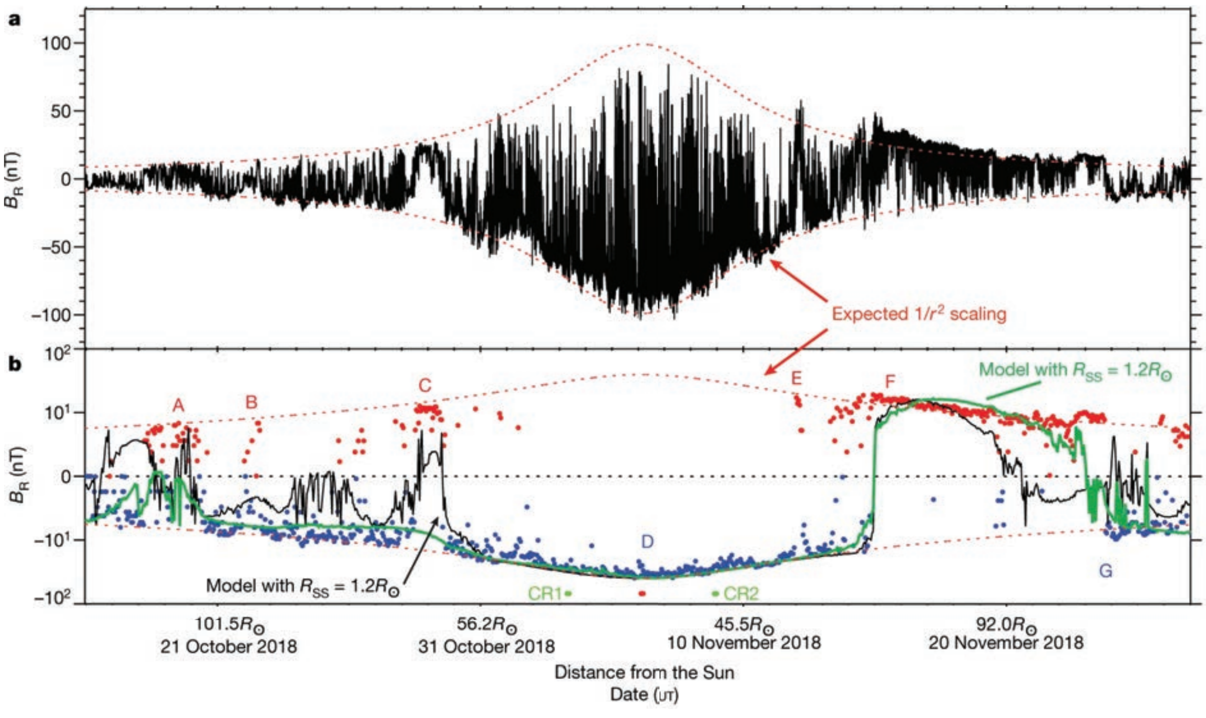

FIGURE B-2 Switchback observations in the solar wind by Parker Solar Probe (PSP). (*Top panel*) In situ measurements of the radial component of the magnetic field by PSP, revealing ubiquitous magnetic switchback structures where the field reverses direction rapidly. (*Bottom panel*) By comparing results from potential field source surface (PFSS) models with source surfaces at 2.0 $R_\odot$ (green) and at 1.2 $R_\odot$ (black) to the large-scale field amplitude (blue and red dots), researchers show that these structures originate in an equatorial polar coronal hole in the lower corona.
SOURCE: S. Bale, S. Badman, J. Bonnell, et al., 2019, "Highly Structured Slow Solar Wind Emerging from an Equatorial Coronal Hole," *Nature* 576:237–242, https://doi.org/10.1038/s41586-019-1818-7, reproduced with permission from SNCSC.

the chromospheric magnetic field in shaping the corona and solar wind? This topic will be explored further in Section B.2.2.

B.1.3 How Do Solar Explosions Unleash Their Energy Throughout the Heliosphere?

The past decade saw a key breakthrough in solar-flare science: the direct mapping of magnetic fields, which power these explosive phenomena, near the acceleration region through the use of the radio astronomical telescope EOVSA (Expanded Owens Valley Solar Array) with microwave imaging spectroscopy (Figure B-3). Prior to this breakthrough, this magnetic energy release could only be inferred indirectly, by comparing the pre- and post-flare photospheric magnetic fields or tracking the motion/evolution of plasma-confining extreme ultraviolet (EUV)/X-ray loops or flare footpoints/ribbons. Multispacecraft observations have also made pivotal advances. The twin Solar Terrestrial Relations Observatory (STEREO) spacecraft combined with the Advanced Composition Explorer (ACE), for example, revealed that solar energetic particles (SEPs) are dispersed in longitude far more than was expected. CMEs are a key driver of space weather, and understanding how they are released and propagate in the heliosphere endures as a major research thrust. Tests of the traditional CME structure paradigm have become considerably more stringent in the past decade, as analyses increasingly utilize data from multiple spacecraft to study structure and kinematics, from PSP showing particles accelerating toward the Sun from the inner heliosphere to Voyager measuring the passage of CMEs in the outer heliosphere.

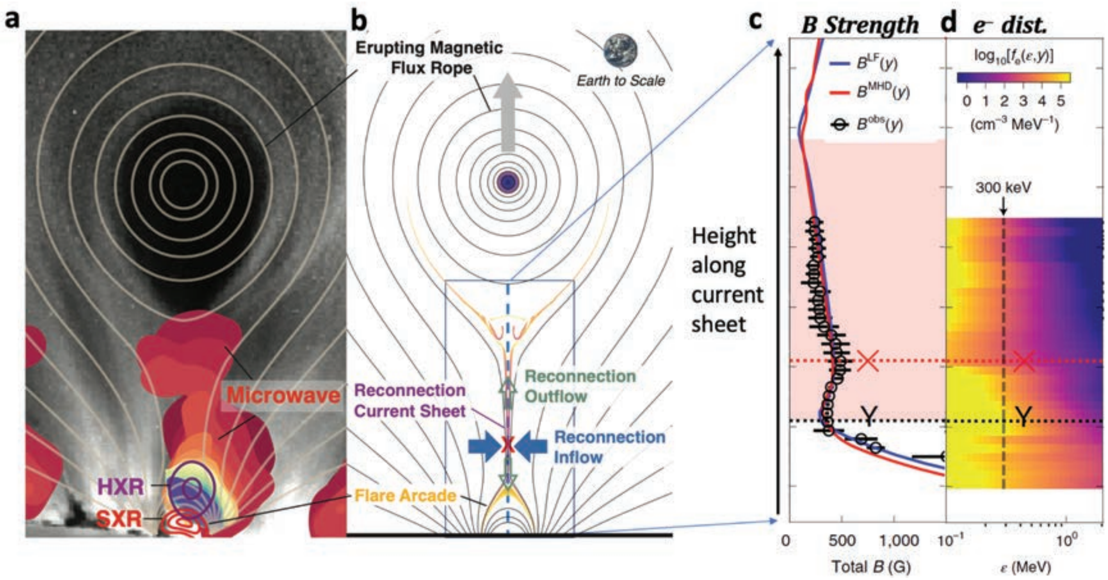

FIGURE B-3 Measurements of magnetic field and high-energy electrons along a reconnection current sheet in an eruptive solar flare. This figure demonstrates the new capability to directly map these key physical parameters of the flare's "central engine" enabled by the microwave imaging spectroscopy observations made by EOVSA (shown as red to purple filled contours in panel (a), which are microwave images at increasing frequencies). Combined with multiwavelength data in EUV and X-ray (background image and open contours in panel (a) and data-informed numerical modeling (panel (b)), the measured coronal magnetic field profile along the current sheet—panel (c), open circles—yields an excellent match with model predictions (blue and red lines). Also, despite their widespread distribution, most of the microwave-emitting energetic electrons are concentrated near the bottom end of the current sheet above the flare arcade (referred to as the "Y" point) but not at the primary reconnection X point (panel (d)).
SOURCES: (*Left and right*) Adapted from B. Chen, C. Shen, D.E. Gary, et al., 2020, "Measurement of Magnetic Field and Relativistic Electrons Along a Solar Flare Current Sheet," *Nature Astronomy* 4:1140–1147, reproduced with permission from SNCSC; (*Middle*) Committee created.

Highlights of additional major science advancements from the past decade include the following:

- *First observations of SEPs backstreaming from distant co-rotating interaction regions:* PSP has provided the first measurements of energetic particles from global solar wind stream interaction regions, and the particles are seen to be moving toward the Sun. The acceleration site is far from the spacecraft, suggesting very efficient transport in the interplanetary magnetic field with a long mean-free path.
- *New multispacecraft observations of CME structure:* In 2014, a CME was observed by no fewer than 10 National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) spacecraft, from the Sun all the way out to Voyager 2 in the outer heliosphere. PSP has provided the first close-up images of transients while they are still near the Sun. These observations are opening new questions about CME structure and evolution.
- *Discovery of large numbers of coronal and precipitating electrons in solar flares:* Researchers discovered that coronal sources in certain solar flares had extremely high nonthermal density. The inferred energy flux of electrons precipitating into the solar atmosphere during the impulsive phase of certain solar flares is also far greater than previously expected, as extreme as ~10^{13} erg s^{-1} cm^{-2}. This value is far outside the realm of the basic assumptions in HXR modeling that has been ubiquitously used for the past 50 years.
- *Discovery of SEPs dispersed widely in helio-longitude:* SEPs from a compact source on the Sun were seen by multiple separate spacecraft near 1 AU and were quite widely separated in longitude. This separation was unexpected because it was thought that SEPs were mostly guided by the Parker spiral magnetic field, but these results indicate that SEPs undergo considerable cross-field transport. It remains unclear how and where this efficient transport occurs. In addition, for energetic electron events associated with HXR flares, it has been found that less than 1 percent of the total energetic electron population managed to escape to interplanetary space, which further underpins the importance of understanding the transport processes from near the Sun and into interplanetary space.

Some of the key questions remaining in this field include the following: What is responsible for the extremely efficient particle acceleration within solar flares? How are SEPs transported into the heliosphere in both longitude and latitude? What causes the wide range of variability in the composition of SEPs? How do CMEs evolve from the Sun to 1 AU? This topic will be explored further in Section B.2.3.

B.1.4 How Is Our Home in the Galaxy Sustained by the Sun and Its Interaction with the Local Interstellar Medium?

The past decade has been a period of tremendous progress in the science of the outer heliosphere. The Voyagers, now making the first in situ measurements of the local interstellar medium (LISM), continue their epic journeys. Each has now crossed the HP, the heliospheric boundary separating plasma of solar origin from that of the LISM. They discovered unusual variations in galactic cosmic rays (GCRs)—particulate radiation mostly produced in supernovae remnants—that permeate the galaxy and enter the solar system where they are modulated by the heliosphere. The Interstellar Boundary Explorer (IBEX) continues to probe the global heliosphere, including an enigmatic enhancement of energetic neutral atoms (ENAs) coming from the outer heliosphere (the “IBEX Ribbon”). New Horizons contributes through the first outer heliosphere measurements of pickup ions (PUIs), produced when an interstellar atom is ionized and representing a nonthermal population in the solar wind, as well as low-energy ions.

Highlights of additional major science advancements from the past decade include the following:

- *Voyagers crossing of the HP:* The Voyager 1 HP crossing in 2012, at a heliocentric distance of 121 AU, was identified by the detection of plasma waves. The local plasma density was determined to be 0.08 cm^{-3}, close to the predicted value. Voyager 2 crossed the HP in 2018 at a distance of 119 AU from the Sun. Voyager 1 does not have a functioning plasma instrument; and while Voyager 2 does, it has not directly measured the LISM plasma. The HP crossing was also identified by the complete disappearance of anomalous cosmic rays (ACRs), a type of cosmic ray produced in the heliosphere and most likely accelerated at the solar wind termination shock (TS). The Voyagers are now measuring the GCR spectrum in interstellar space, unmodulated by the heliosphere.

- *Proof that the heliosphere responds to solar-cycle variations:* IBEX ENA maps collected over the past decade have revealed a sudden and intense heating of the heliosheath resulting from a large increase in dynamic pressure of the solar wind after a long period of weak solar activity, convincingly demonstrating the heliospheric response to changes in solar activity (Figure B-4). The IBEX Ribbon as well has changed with time on the scale of years, reflecting changes from the solar cycle.
- *The IBEX Ribbon originates in a region of trapped solar wind beyond the heliopause:* The IBEX Ribbon is a feature that appears in ENA maps of the sky that is oriented along the locus of points where outward lines-of-sight from the Sun are perpendicular to the interstellar magnetic field (ISMF) draped around the heliosphere. Numerous theories have been proposed in the past decade to explain the origin of the Ribbon. A preponderance of evidence now suggests the Ribbon results from a multistep "secondary ENA" process whereby outgoing neutralized solar wind travels unimpeded beyond the heliopause is then reionized and captured by the draped ISMF, and then reneutralized several years later, producing a population of secondary ENAs, some of which return to the inner heliosphere and observed as the Ribbon. Research is ongoing to explain the details of exactly how the ion population is captured and retained.
- *First measurements of the magnetic field in the LISM:* The magnetic field increased at the HP crossing, but, surprisingly, its direction only changed slightly, counter to predictions. The field strength in the LISM measured by Voyager 1 was ~4.6 μG and was later observed to be somewhat higher by Voyager 2, at ~5.8 μG. This implies that the magnetic pressure is some 40 percent different at the two separate

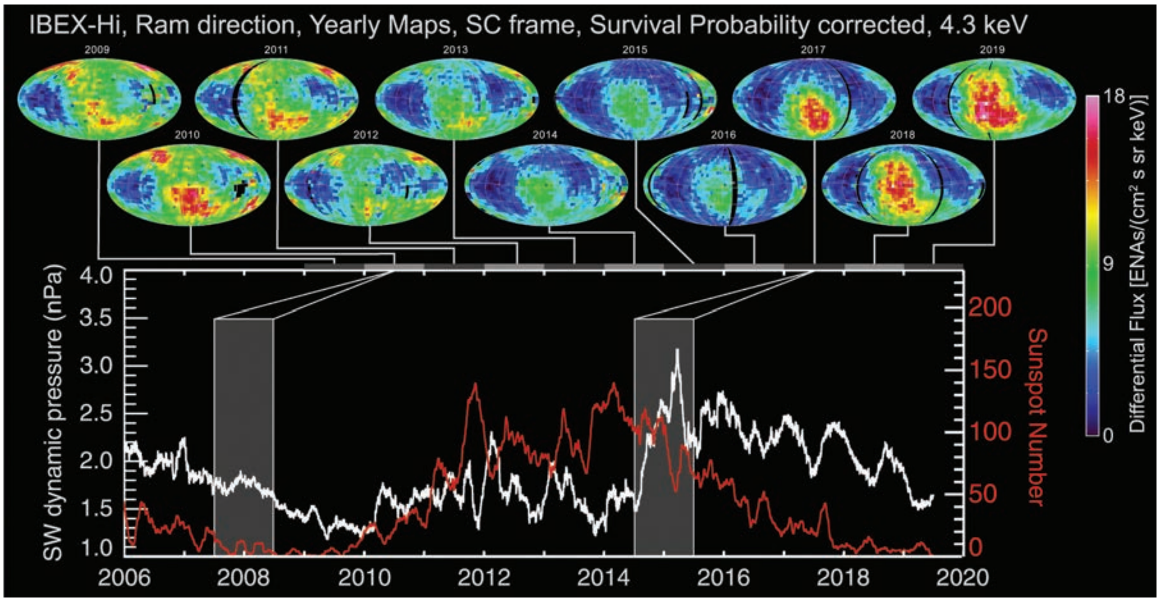

FIGURE B-4 Interstellar Boundary Explorer (IBEX) all-sky maps of energetic neutral atom (ENA) flux at 4.3 keV over a full solar cycle (2009–2019) compared to the time series of the smoothed sunspot number (bottom, red trace) and solar wind dynamic pressure at 1 AU (bottom, white trace). In 2017, a strong ENA flux enhancement suddenly appears in the nose direction of the heliosphere and expands rapidly through 2019. The enhancement is associated with a rapid increase in the solar wind dynamic pressure ~2–3 years previously in 2014, consistent with the time delay expected by a heliosheath that is ~100 AU from the Sun. This demonstrates that the heliosheath responds rapidly to changes in solar wind output.
SOURCE: D.J. McComas, M. Bzowski, M.A. Dayeh, et al., 2020, "Solar Cycle of Imaging the Global Heliosphere: Interstellar Boundary Explorer (IBEX) Observations from 2009–2019," *Astrophysical Journal Supplement Series* 248(2):26, https://doi.org/10.3847/1538-4365/ab8dc2. © AAS. Reproduced with permission.

crossing points, suggesting an asymmetry in the way in which the LISM magnetic field drapes around the heliosphere. The field strength of ~4.6–5.8 μG is larger than predictions, but within the range of expected variations owing to LISM turbulence.

- *Discovery of shock-like plasma disturbances in the LISM:* The plasma waves that led to the discovery that Voyager 1 had crossed the HP have been observed at other times as well, deeper into the LISM. These waves resemble shock-like structures and are certainly large-scale global disturbances passing the spacecraft, much thicker than shocks observed inside the heliosphere for many years.

Some of the key questions remaining in this field include the following: What is the geometric shape of the heliosphere? How are GCRs modulated across the HP and within the heliosheath? What is the PUI distribution across the termination shock and within the heliosheath? This topic will be explored further in Section B.2.4.

The panel considered the prodigious achievements of the Sun and heliosphere community, the valuable inputs provided through 187 contributed community input papers, and the space- and ground-based capabilities available now and in the near future, to assess the current state of the field. This assessment was used to identify the science goals moving forward for the community, including near-term PSGs, a longer-range goal (LRG), and emerging opportunities (EOs). The panel identified four PSGs, each described in Section B.2. The LRG is detailed in Section B.3. Two EOs are introduced in Section B.4. The current and envisioned guiding research activities, including enabling space-based mission concepts and ground-based facilities for the next decade, are described at length in Section B.5. Included in this last section are considerations addressing broader community needs and enabling opportunities.

B.2 PRIORITY SCIENCE GOALS

The four Sun and heliosphere PSGs are described in this section along with a description of the research and analysis development programs supporting these activities. For each goal, the panel lays the groundwork for the relevance and importance of the science and describes the current research activities for each objective. The panel identifies prevalent current and planned observational resources that are available, both space- and ground-based, and outlines the state of theory, modeling, and simulations relevant to addressing these goals. Last, the panel discusses how these goals are motivated by the current state of the field and describes their contribution to system-level science.

B.2.1 Priority Science Goal 1

Since the discovery that the solar photosphere is covered by magnetic fields in 1908, scientists have come to realize that the overwhelming majority of solar variability is driven by magnetism. This variability happens over decadal timescales in the form of the solar magnetic cycle, quasi-annual/quasi-biennial timescales of solar activity in the form of solar "seasons," weeks-to-months timescales in the form of active regions emergence and decay, and minutes-to-hours timescales in the form of flares and CMEs. The question of how the Sun maintains its magnetic activity globally has pervaded all previous decadal surveys in different guises, and there has been substantial progress in the ability to observe and simulate all of these different timescales. However, owing to lack of knowledge of flows and fields in the polar regions and greater depths (Figure B-5), the understanding of the solar dynamo and activity cycle and their connections to the evolution of the 3D corona remain crucially incomplete.

While global measures of meridional circulation as a function of latitude and depth have continued in the past decade, focus has also extended on determining the role of local active regions' flows in modulating the global meridional circulation as a function of latitude and time. Long-term data collection efforts have helped in deriving the variation in differential rotation and variation in the tachocline properties as a function of the solar cycle. Progress has been made in inferring the emergence and existence of active regions on the far-side of the Sun. One of the newest discoveries of helioseismology over the past decade has been detecting Rossby waves and other inertial waves in low latitudes. How the flows and waves behave at the polar latitudes and globally around the whole Sun and whether longitude dependence exists in the meridional circulation are not known yet.

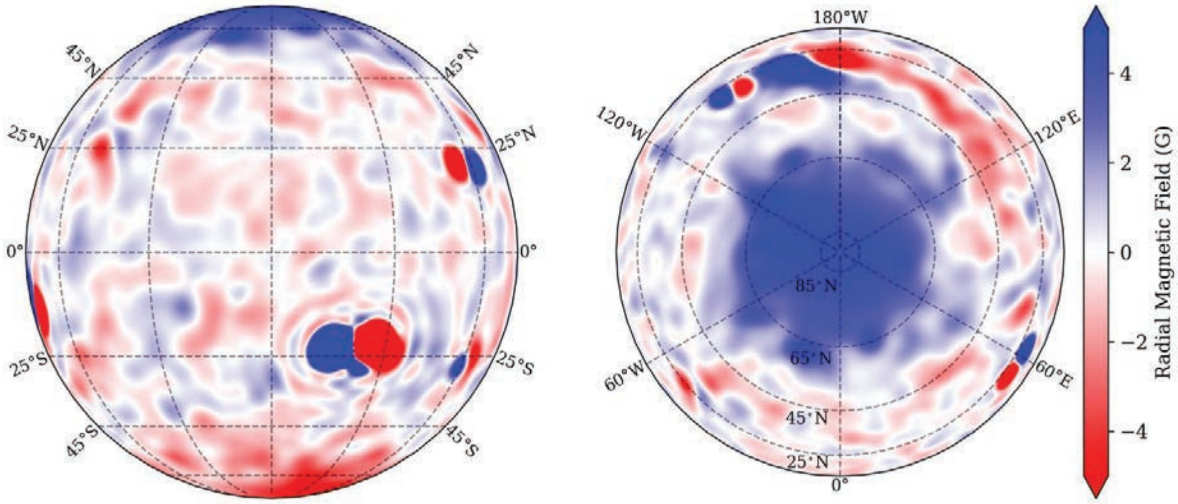

FIGURE B-5 (*Left*) A snapshot of the surface distribution of magnetic fields from a solar surface magnetic field evolution model depicting a perspective close to the plane-of-the-ecliptic (solar obliquity ignored). (*Right*) The equivalent perspective from the top of the Sun's north pole reveals details of the polar cap missing from the low-latitude perspective. A mission that can navigate to at least 60 degrees above (or below) the ecliptic plane would reveal these details, constrain the high-latitude dynamics and return accurate measurements of plasma flows and magnetic field distribution at the poles that govern solar activity and power fast solar winds.
SOURCE: Nandy et al. (2023), https://doi.org/10.3847/25c2cfeb.1160b0ef. CC BY 4.0.

PSG 1 (Table B-1) captures the community's need to push forward the understanding of what makes the Sun a star, with an emphasis on polar measurements. The objectives highlight the critical role that solar plasma flows and magnetic fields play in driving all observed solar phenomena from the photosphere to the edge of the heliosphere and stress that the solar poles remain outside of observational capabilities, thus representing one of the final observational frontiers in solar physics.

Current Research Activity

Priority Science Goal 1, Objective 1.a

The solar poles seed the magnetic fields that generate and shape future solar cycles. However, there is limited understanding on where and how the polar fields connect to dynamo generation across the whole convection zone. Achieving this objective requires direct observations of the polar fields, including information about the subduction mechanisms that connect polar fields and toroidal belts (such as meridional circulation). It also requires a better understanding of the polar differential rotation, including the possible existence of a polar vortex and the thickness of the tachocline at the poles (Figure B-6).

TABLE B-1 Sun and Heliosphere Priority Science Goal (PSG) 1 and Objectives

PSG 1 (of 4)	Objectives
How does the Sun maintain its magnetic activity globally from *pole to pole*?	a. Determine the role of the polar and high-latitude magnetic fields and flows in the evolution of the solar dynamo. b. Determine how dynamo-generated fields emerge through the surface and shape the three-dimensional structure of the solar atmosphere and heliosphere. c. Determine the nature of global flows and inertial waves at all latitudes, down to tachocline depth, and their relationship to the solar dynamo. d. Determine how solar magnetism changes over the solar cycle, from the solar interior through the highly coupled solar atmosphere.

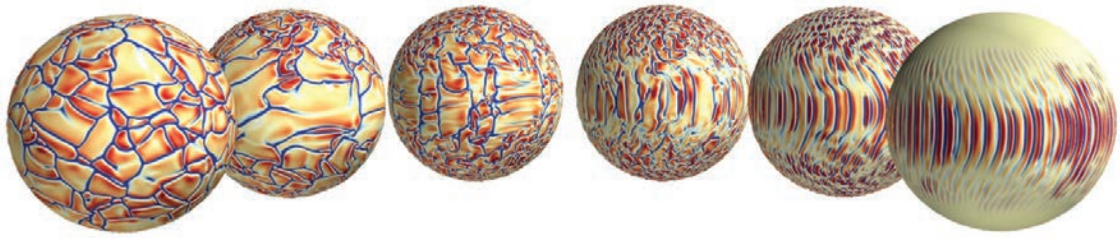

FIGURE B-6 Three-dimensional rendering of simulated solar-like convection realized under different Rossby numbers. Regions of upflow (downflow) are rendered in red (blue). As rotational influence increases from left (high Rossby number) to right (low Rossby number), convective patterns become increasingly more helical and columnar. This figure highlights how polar observations can help distinguish between different solar convection regimes.
SOURCE: Featherstone et al. (2023), https://doi.org/10.3847/25c2cfeb.240cbaca. CC BY 4.0.

Priority Science Goal, Objective 1.b

Magnetic fields, generated by the solar dynamo, manifest at the surface in the form of active regions. Extensive efforts have been made to model the movement of magnetic flux from the dynamo layers to the surface by convective instability and magnetic buoyancy effects. Their emergence and evolution drive the evolution of coronal structure and energetics. To accomplish this objective, it is necessary first to understand what processes govern magnetic flux emergence through the surface and their specific latitude–longitude distribution, and then to integrate modeling efforts combining flux emergence from dynamo layers to the surface with the evolution of the global corona. This work needs to be combined with a sustained effort to measure magnetic fields directly in the chromosphere and corona, as well as to expand observational capabilities to observe the full solar surface, with multiviewpoint observations to jointly build a comprehensive picture of the entire process.

Priority Science Goal, Objective 1.c

While global flows, like differential rotation and meridional circulation (two major ingredients of solar dynamo models), have been measured successfully at the surface up to a latitude of about 60 degrees through helioseismic techniques, knowledge about their profiles in latitude, longitude, and depth is still lacking. Solar Rossby waves and inertial oscillations were detected within the past decade and have been shown to nonlinearly interact with mean (longitude-averaged) flows and magnetic fields in a complex fashion, which may explain the observed nonaxisymmetric (longitude-dependent) distribution of surface active regions. This nonlinearity is just one example of the key questions raised concerning the interaction between these waves and oscillations that need to be explored in the next decade.

A topmost priority in the next decade is to refine helioseismic techniques to enable new important measurements. These techniques include the ability to measure the thickness of the tachocline as a function of latitude, to determine whether global flows have longitudinal structures and to distinguish between inertial oscillations and large-scale convective motions as a function of convection zone depth. This capability will allow us to finally resolve the long-standing inconsistencies between helioseismic observations of convective velocities and global convective model-outputs.

Priority Science Goal, Objective 1.d

Every aspect of the way the Sun drives variability in the solar system is connected to the solar cycle via active region emergence and decay. Achieving this objective thus requires the coordination between surface and helioseismic measurements to infer changes in the subsurface toroidal field. Also needed is an understanding of how changes in large-scale solar flows determine subsequent changes at the surface and in the atmosphere. It is imperative to modernize historical data such that they can be combined with current data to produce a long-term

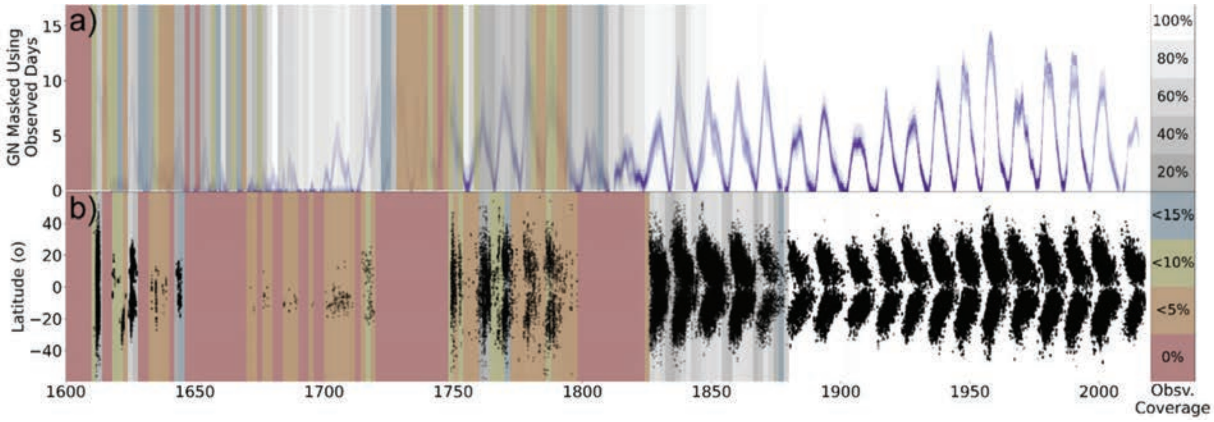

FIGURE B-7 Group sunspot number (a) and butterfly diagram (b) displaying the observational coverage of each year between 1600 and 2019. Color shading highlights the difference in coverage and quality between the historical and modern periods. It also highlights the importance of taking advantage of available historical data.
SOURCE: A. Muñoz-Jaramillo and J.M. Vaquero, 2019, "Visualization of the Challenges and Limitations of the Long-Term Sunspot Number Record," *Nature Astronomy* 3:205–211, https://www.nature.com/articles/s41550-018-0638-2, Springer Nature.

homogeneous observational baseline (Figure B-7), including as many sunspot cycles' worth of observations of magnetic fields, plage, coronal bright points, and coronal structures as possible.

Observational Resources

To study the Sun's internal structure, SDO's Helioseismic and Magnetic Imager (HMI) and the Solar and Heliospheric Observatory's (SOHO's) Michelson Doppler Imager (MDI) (MDI until 2011) make full-disk measurements from which differential rotation, meridional circulation, and Rossby waves are inferred from frequency shifts in acoustic modes of the Sun. These measurements are also used to study domains from the Sun's outer atmosphere to the solar wind, spanning the spatial progression from small-scale local dynamics to global dynamics in the form of synoptic maps. Although SDO/HMI observations of the evolution of flows and magnetic fields inform all four objectives, their range is limited to latitude below 60 degrees and to the visible disk of the Sun.

The ground-based instruments of the Global Oscillation Network Group (GONG), a network of six identical observatories distributed all over the globe, guarantee a continuous coverage of the Sun, providing measurements similar to SDO/HMI (although at a lower spatial resolution). The Sun's internal oscillations, caused by sound waves that travel through its interior, are studied to learn about the physical properties of the Sun's interior, such as its temperature, pressure, composition, rotation, meridional circulation, and inertial waves. The GONG high-resolution spectrographs provide full-disk, high-cadence Doppler shift maps caused by these oscillations for helioseismology studies. GONG measurements of the line-of-sight photospheric magnetic field over the full disk, at a ~10 min cadence, are used to produce extrapolated models of the 3D coronal and heliospheric magnetic field.

Like all full-disk instruments observing from the ecliptic, GONG has latitudinal coverage for flows and fields up to roughly 60 degrees north and south. Hence, GONG can also contribute to achieve all four objectives. Great benefit has been achieved by having HMI and GONG operating simultaneously using different instrumental techniques allowing mutual validation of helioseismic results. While the use of helioseismic holography techniques has made far-side imaging possible from these instruments' data, in order to make further progress in the next decade, observations from 65 degrees latitude up to the poles as well as simultaneous views of 360 degrees longitude are necessary.

The Solar Orbiter (SO) mission includes a magnetograph (Polarimetric and Helioseismic Imager [PHI]) that can measure complex near-surface flows, meridional flows, and differential rotation at the surface, up to 65 degrees latitude and an EUV imager (EUI) that will measure and characterize plasma flows that transport magnetic fields. The out-of-the-ecliptic phase of SO, beginning in 2027, would provide some information about polar regions and hence new constraints for solar dynamo models, but the observations will only cover a few weeks per year. In 2030, SO is set to reach an orbital inclination of 34 degrees, which will give a better view of the poles but yet will not allow for the multimonth monitoring of the polar flows needed to be detected by helioseismology, and hence comprehensive understanding of dynamo and polar field evolution will remain incomplete.

The Hinode mission's Solar Optical Telescope (SOT) infers the Sun's magnetic fields up to 70 degrees latitude to study what drives solar eruptions and powers the solar atmosphere. SOT measures Zeeman/Stokes parameters to obtain both strength and direction of the magnetic fields associated with the eruptions. This instrument has been successfully resolving polar fields for more than a solar cycle up to about 70 degrees (beyond which the spatial resolution decreases owing to foreshortening) and will remain the best source of polar field measurements until a truly polar mission is implemented. Complementary Hinode instruments produce X-ray images and EUV spectroscopy to diagnose temperature and pressure in the corona above the photospheric fields.

The Polarimeter to Unify the Corona and Heliosphere (PUNCH) is an upcoming (~2025) Small Explorer (SMEX) mission developed to understand how the mass and energy in the Sun's corona form the solar wind and globally evolve. PUNCH consists of four synchronized Earth-orbiting satellites, each containing four instruments, with the goal of producing a continuous picture of the whole inner heliosphere.

The Upgraded Coronal Multi-channel Polarimeter (UCoMP) is a ground-based 20 cm aperture Lyot coronagraph with a Stokes polarimeter. It can image the intensity, linear Stokes polarization, Doppler shift, and line width across coronal emission lines in the visible and near-infrared (IR), up to 2 $R_\odot$ (1.56 $R_\odot$ in the polar direction). Joint analysis of different emission lines provides information about global coronal variations of density and temperature as well as dynamics and magnetic field direction in the plane of the sky. Recent studies on the propagation of waves in the low corona have provided estimates of the magnetic field strength in defined regions.

The Kodaikanal Solar Observatory (KoSO) has one of the world's longest-term digitized full-disk solar data archives in white light (1904–2017), Ca II K (1904–2007), and H-α (1912–2007) enabling analysis of solar flows, meridional circulation, and differential rotation as well as the evolutionary patterns of polar faculae and active regions. The images have been recorded with optical telescopes, including a 15-cm-aperture photoheliograph and twin 6-cm-diameter spectroheliographs, which provide the full-disk photographs of the Sun in K-α and H-α. Mount Wilson Observatory has similar records.

Theory, Modeling, and Simulations

Significant theoretical effort to understand how the Sun maintains its magnetic activity globally has enabled us make substantial progress during the past decade—thanks to significant improvement to models of the solar magnetic field through several NASA programs: HSR (Heliophysics Supporting Research), HTMS (Heliophysics Theory, Modeling, and Simulations), LWS-FST (Living With a Star Focus Science Topic), LWS Strategic Capability, and NASA Diversify, Realize, Integrate, Venture, Educate (DRIVE) Science Centers, as well as National Science Foundation (NSF) programs (e.g., Next-Generation Software for Data-driven Models of Space Weather with Quantified Uncertainties [SWQU], Advancing National Space Weather Expertise and Research toward Societal Resilience [ANSWERS], and Science and Technology Centers [STC]), and an increased level of computational power.

While scientists are still not close to a global turbulent MHD simulation of the solar interior, surface, and atmosphere that can simulate decades of evolution, all the different models used to understand solar magnetism have clearly begun to overlap in the relevant spatial and temporal scales they simulate, as well as reproducing solar-like behavior with a fidelity that was not possible 10 years ago.

Surface flux transport simulations (simulations of the surface radial magnetic field, driven by prescribed flux emergence and flows) have transitioned from modeling turbulent convection as a diffusive process to the inclusion of realistic convective turbulent flows. This advancement in modeling techniques, coupled with better means for assimilating solar magnetograms (and far-side EUV images), has resulted in simulations that bear an uncanny resemblance to real observations and are used to fill observational gaps on the solar far-side.

High-resolution turbulent convective simulations (full 3D MHD simulations of wedges of the solar convection zone encompassing the near surface layers and photosphere) now involve significantly larger wedges and higher resolution and coupling of subsurface convection with simulations of the lower corona. This improvement has enabled the simulation of a wide range of solar magnetic phenomena (e.g., quiet Sun, sunspots, and flux emergence) as well as that of surface solar observables that are almost impossible to distinguish from real observations.

Global anelastic simulations (3D MHD simulations of the part of the global convection zone in which the global dynamo operates) have attained solar-like oscillatory behavior and routinely produce solar-like cycles. This realistic reproduction has enabled the systematic exploration of simulated stars with solar-like cyclic behavior, which in turn has sharpened the focus on the importance of rotation and convection in the establishment of solar global flows like differential rotation (including or not a tachocline), meridional circulation, and the roles they play in the global dynamo.

Kinematic mean-field dynamo models (simulations of the mean solar magnetic field that abstract the turbulence velocity field through an electromotive force and turbulent diffusion) have been generalized from two-dimensional (2D) to 3D models. This advance has led to synergies between mean-field models that can separate small-scale turbulence and large-scale dynamics along with full 3D MHD simulations. Such a step forward has enabled breakthroughs by simulating buoyancy instability-driven emergences of bipolar magnetic regions, torsional oscillation patterns, and extended solar cycle. What is still lacking is input of physical processes happening in the polar regions as well as comparisons between model-outputs and observations there.

Atmospheric Rossby waves (the large meandering patterns occurring in the atmospheres of rotating celestial bodies owing to variation of the Coriolis force with latitude and/or differential heating from the Sun) have been used for terrestrial weather prediction for several decades. By contrast, solar Rossby waves were an unanticipated observational discovery made only in the middle of the past decade. Since then, the development of solar Rossby waves theory and modeling as well as further observational evidence grew quickly, and their nonlinear dynamics have given hints on the roles Rossby waves play in determining the spatio-temporal distribution of active regions. Nevertheless, it is not known for sure yet where they are generated and exactly how they manifest at the surface and solar atmosphere, and so it is necessary to further develop modeling capability. What roles do Rossby waves and other inertial waves play in short-term, decadal, and long-term solar variability, and thus in space weather and climate? To how high a latitude do Rossby waves reach, and what are their longitude patterns around the whole Sun?

The NASA DRIVE Science Center "COFFIES," led by Stanford University, is producing cutting-edge global models for studying the "Consequences Of Fields and Flows in the Interior and Exterior of the Sun," with an internationally collaborative team of 85 researchers to expand the understanding of the Sun to simulate where and when active regions emerge and to develop the capability to forecast activity cycles and solar magnetic variability. In parallel, a non-U.S. "Whole Sun Project," funded by the European Research Council, is a collaborative effort among European universities and institutes to develop a complete Sun model to determine over the next 6 years how the interior magnetic field is generated and how it creates sunspots on its surface and eruptions in its highly stratified atmosphere.

Motivation for the Goal

At the beginning of the past decade, the researchers in this field still had an incomplete understanding the processes that determine the global distribution of magnetic fields, their cyclic evolution, and the spatio-temporal patterns of polar fields, all of which are necessary to understand and predict the next solar activity cycle. Synoptic maps derived from through observation from ground-based and space-borne magnetograms, such as GONG, SDO/HMI, successfully provided observations of photospheric magnetism and global flows (differential rotation and meridional circulation) up to about 60 degrees, on both front and back sides, as well as how active region inflow cells modulate to create time-variation in meridional flow. Differential rotation is also accurately determined up to 60 degrees, as well as the global coronal structure, but it is not known yet whether (1) the polar regions spin up or spin down, with associated vortices like Jupiter, or (2) a reverse-flow exists beyond 60 degrees, and/or there is a longitude dependence in this flow. Hinode/SOT showed that the pole is not filled with a diffuse field, but it contains highly concentrated unipolar patches. STEREO A and B provided invaluable synchronous observations, which led to discovery of inertial waves. (Unfortunately, such observations were extremely limited owing to the loss of STEREO B.) Currently, the integrated polar flux is the best predictor of the subsequent solar cycle strength, which is highly dependent on global flows, but there is no clear evidence as to whether this relationship is causal or correlational.

PSG 1 emphasizes the need to carry out studies of the Sun that have long-term global coverage. There are currently two major gaps in observations: (1) measurements are largely limited to the Sun–Earth line; that is, synchronous observations of near and far-side are severely limited; and (2) with ground-based and space-borne instruments only in the ecliptic plane, observations of polar regions are severely limited. Expanding observational coverage to the poles and the far-side of the Sun is necessary to probe deeper into the interior of the Sun, to measure the full open magnetic flux in the heliosphere, and to determine how active regions' magnetic fields are distributed around the Sun and drift toward the poles to cause polar fields. Pole-to-pole observations at all solar longitudes along with simulations will be essential in the next decade toward developing a complete understanding of the dynamo generation of magnetic fields and their emergence at the photosphere (including their spatio-temporal distribution), and how they shape the global corona and heliosphere.

System-Level Science Contributions

PSG 1 is intimately connected with all the SHP science goals, including the SHP LRG and EOs. There are three main points of synergy: variability, energetics, and context.

First, variability in the decadal, quasiannual, and weeks/months timescales provides the backdrop against which both magnetic and radiative environments in the corona and heliosphere are established (PSG 2); it determines the frequency of explosive events and the heliospheric structure in which they dissipate in the solar system (PSG 3); and it determines the environment in which cosmic rays are propagated from outside the heliosphere (PSG 4).

Second, energetics driven by the spatio-temporal evolution of global magnetic fields provide the energy and structure that determines the origin and properties of the solar wind (PSG 2) and determines the relative intensity of explosive events (PSG 3).

Third, the observation of global magnetism and the way it structures heliospheric plasma is necessary to provide context to direct measurements of coronal and heliospheric magnetic fields (LRG) and well-measured global plasma flows and magnetism (from pole to pole) will play a critical role in constraining the dynamic regime that contextualizes what kind of star the Sun is (EO 1).

B.2.2 Priority Science Goal 2

The generation of the solar atmosphere and its expansion into the extended heliosphere depend on a complex interplay of multiple elements even in periods of low solar activity, including subsurface and convective flows, magnetic, sound and plasma waves, and, most importantly, the ever-changing magnetic field that permeates it. In order to understand such a complex and interconnected system, researchers need to jointly address fundamental phenomena, such as the transport and dissipation of nonthermal energy from the photospheric reservoir to produce and energize the dynamical and spatially structured chromosphere and corona; the creation of the solar wind and its spatio-temporal structuring at different scales; and the structure and evolution of the magnetic field in the outer atmosphere and heliosphere.

Recent developments in the capability to infer the chromospheric and coronal magnetic field strength and topology, as well as novel observations from multiple vantage points within the ecliptic, are paving the way to a "system science" approach. Together with a number of complementary facilities and missions scheduled to commence or ramp up operation in the next few years, this capability will allow researchers to causally connect the fundamental phenomena creating the solar atmosphere as a whole—from the solar surface to the heliosphere.

PSG 2 (Table B-2) captures the community's need to more comprehensively understand the physical interconnections linking the Sun through the heliosphere. This goal also has obvious ties to the broad astrophysical questions

TABLE B-2 Sun and Heliosphere Priority Science Goal (PSG) 2 and Objectives

PSG 2 (of 4)	Objectives
How do the Sun's magnetic fields and radiation environments *connect* throughout the heliosphere?	a. Demonstrate how photospheric and chromospheric dynamics drive the corona. b. Determine the role quasi-steady processes play in the heating of the solar corona and the acceleration of the solar wind and suprathermal particles. c. Understand how the magnetic field of the corona and inner heliosphere is structured, how it evolves, and how it connects to and influences the interplanetary magnetic field on varying timescales. d. Trace the origin of solar wind variability, and identify the extent to which it is owing to local kinetic processes or underlying global solar activity.

of how stars create their atmosphere and influence their environment and how this determines the habitability of stellar systems besides our own.

Current Research Activity

Priority Science Goal 2, Objective 2.a

The constant interaction between photospheric flows and surface magnetic fields is ultimately responsible for structuring the solar corona both in quiet and active regions. Yet researchers are just starting to uncover the detailed operation of many different processes, including how the dynamics of small-scale magnetic elements (at granular sizes and below) influence the response of the upper atmosphere, and how the highly variable chromospheric magnetic topology and plasma density mediate the transfer of mass and energy to the corona and beyond. Substantial progress on this topic will require a multipronged approach, including high-resolution, high-cadence measurements of both the photospheric and chromospheric vector magnetic field; multiwavelength diagnostics of the coronal emission; reliable inversion techniques to obtain the thermodynamic plasma parameters and their evolution; as well as realistic numerical simulations of the highly coupled solar atmosphere.

Priority Science Goal, Objective 2.b

Outside of transient, explosive events like flares, the Sun maintains a multi-million-degree corona in both quiet and active regions that are characterized by closed magnetic configurations. Within coronal holes, dominated by open fields, temperatures around 1 MK are sustained. The exact mechanisms that heat the corona and accelerate the solar wind continue to be debated, but there is a growing body of evidence that they operate on small spatial and temporal scales, mediated by the overall coronal magnetic structure. Furthermore, many of the physical transitions and processes that govern the acceleration of coronal outflow are thought to occur in the middle corona (1.5–6.0 $R_\odot$; see Figure B-8), a region currently lacking significant observational coverage. High-cadence diagnostics of the plasma (temperature, density, composition) and particle (distribution, localization) throughout the corona, including the middle corona, will need to be applied in concert with high-resolution data from the lower atmosphere, as well as with in situ measurements of fields and plasma properties. Polar observations, both in situ and remote sensing, will be extremely valuable as they provide a direct view of the processes leading to the acceleration of the fast solar wind.

Priority Science Goal, Objective 2.c

The coronal and heliospheric magnetic field provide a pathway for energetic particles accelerated near the Sun to expand out into the heliosphere, at times over wide latitudinal and longitudinal ranges, indicating complex magnetic connections in the inner heliosphere. Both the structure of the coronal field and its temporal evolution as well as the nature of the extension of the coronal field into the heliosphere via the interplanetary magnetic field are currently poorly understood, and studies rely mostly on extrapolations from surface magnetic fields and global models. This suffers from a number of limitations, including the fact that the usual assumption of force-free

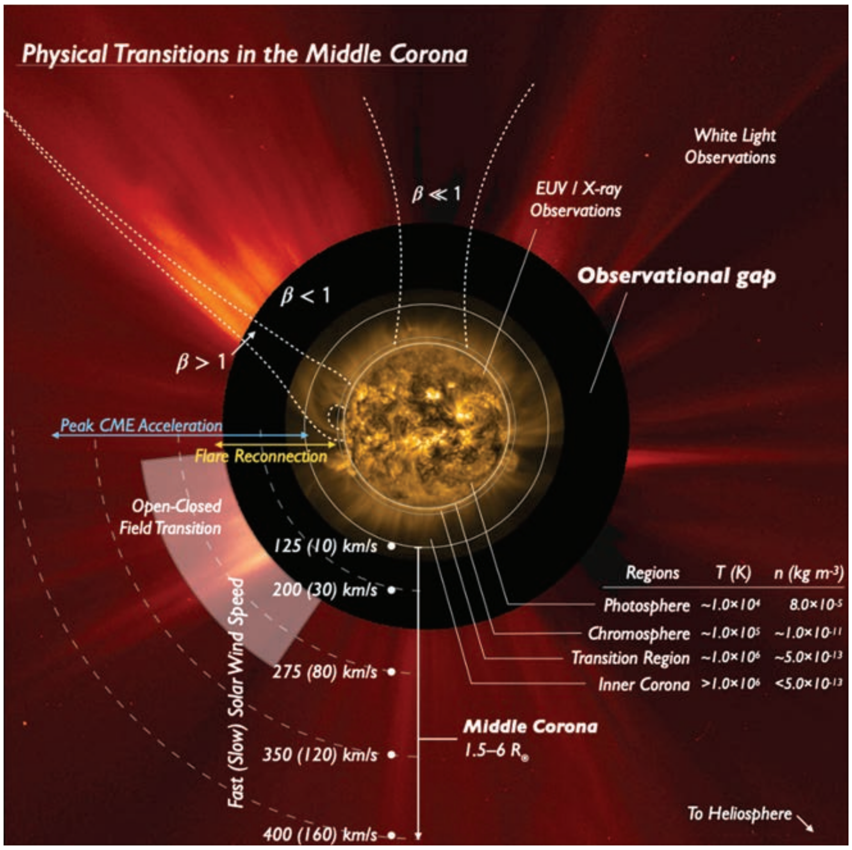

FIGURE B-8 Many physical processes governing the configuration of the corona and the acceleration of the solar wind occur in the middle corona. Shown are Sun Watcher with Active Pixels and Image Processing (SWAP) (Halain et al. 2013; Seaton et al. 2013) and Large Angle and Spectrometric Coronagraph (LASCO) (Brueckner et al. 1995) composite images highlighting the middle corona, its physical transitions, and the observation gap where temperature, density, and composition measurements are needed to probe the details of coronal energy transfer.
NOTE: CME, coronal mass ejection; EUV, extreme ultraviolet.
SOURCES: West et al. (2022b), https://doi.org/10.1007/s11207-023-02170-1. CC BY 4.0; Sun image from West et al. (2022a), https://doi.org/10.1007/S11207-022-02063-9. CC BY 4.0.

field is not satisfied in the photosphere. A concerted effort at improving extrapolations by using multiheight field measurements, as well as reliably estimating the coronal field and its evolution using a variety of diagnostics, together with measurements of in situ fields and plasma properties in different points of the inner heliosphere, are necessary to make substantial progress.

Priority Science Goal, Objective 2.d

The solar wind is observed to vary over a range of spatial and temporal scales, with processes interacting across these scales. Most measurements of solar wind variability have been conducted with single spacecraft observations, making it difficult to disentangle spatial and temporal variations. Additionally, determining the source of the variability is a challenge as both heliospheric processes and processes in the solar corona can imprint their changing plasma characteristics on the wind. Faster solar wind from coronal holes is observed to be less variable in many ways than slower solar wind from outside of coronal holes and from equatorial regions. Determining the origin of this variability, whether it is owing to local kinetic processes or underlying global solar activity, is critical to understand the connection between the solar atmosphere and the solar wind, as well as the influence/interaction of the solar wind on/with the space environments of solar system objects throughout the heliosphere.

Observational Resources

Many of the existing and near-future solar missions and ground-based facilities are relevant to PSG 2. Notably, during the past decade there has been an increased focus on the complementarity of these multiwavelength, multidiagnostics facilities that attempt to relate phenomena observed in the upper atmosphere and solar wind to their source regions at the solar surface.

Large-aperture ground-based telescopes equipped with Adaptive Optics systems, such as the Dunn Solar Telescope (DST), the Swedish Solar Tower (SST), the 1.6 m Big Bear Solar Observatory Goode Solar Telescope (BBSO/GST), or the recently commissioned 4 m Inouye Solar Telescope can observe the solar surface at very high spatial resolution. This resolution is necessary to clarify how small-scale phenomena of magneto-convective origin might structure the upper solar atmosphere, both in quiet and active regions. As a relevant example, recent remarkable GST observations of the photospheric magnetic field at scales of less than 200 km on the Sun highlighted how dynamic minority-polarity intrusions in the magnetic network actively cancel with the dominant polarity field, driving an upper atmospheric response in the form of intermittent chromospheric spicules and coronal jetlets, which are likely an important source of energy injection into the corona. Spicules have indeed been observed with IRIS and SDO to be heated to transition region and even coronal temperatures, while jetlets have been observed by SDO's Atmospheric Imaging Assembly (AIA) as intermittent hot-plasma outflows, possibly related to the nascent solar wind. A similar picture, detailing how quiet-Sun coronal loops connect and respond to surface regions harboring weak and rapidly evolving (<5 minutes) magnetic elements, has been inferred by using SO/PHI and EUI. The 4 m optical/IR Inouye, recommended in previous decadal surveys and currently in the operational commissioning phase, is now truly pushing this frontier by showing that the relevant spatial scales might be even smaller. Figure B-9 shows how the footpoints of magnetic flux tubes, identified by intergranular bright points, are actually only 30–50 km wide at the solar surface.

Measurements of flux tube dynamics (including transverse and rotational motions) and of their photospheric field strength and topology will be necessary to assess the energy available in these magneto-convective phenomena. Stereoscopic observations of these photospheric magnetic fields with PHI, together with instruments along the Sun-Earth line, will allow for regular removal of the 180 degrees ambiguity in the orientation of the transverse component even for small scale features, greatly aiding in the derivation of the chromospheric fields' topology. The coronal response might be estimated using coronal imagers such as SDO/AIA (assuming they will continue operating) but to make sustained progress, a spatial resolution of order 20–300 km (depending on the wavelength and height), as demonstrated by the High-resolution Coronal imager (Hi-C) in previous rocket flights, and as now provided by SO/EUI, will be necessary. Thus, coordinated campaigns will be a critical tool to ensure that common targets are observed by multiple facilities during the relatively short remote sensing windows planned for SO (three 10-day periods per orbit). In the near future, the high-cadence EUV context-imager of the Multi-slit Solar Explorer (MUSE) and the EUV High-throughput Spectroscopic Telescope (EUVST) missions (launch currently set for 2027 and 2028, respectively) will be momentous for this PSG, both providing complementary EUV spectroscopy with high spatial (down to ~200 km) and temporal (few seconds) resolution.

Ultimately, however, reliable assessments of the energetics of events in the upper solar atmosphere require information on density, temperature, and velocity—that is, spectroscopical capabilities. Chromospheric and transition region spectra acquired with the IRIS UV imaging-spectrograph, in operation since 2013, have contributed multiple critical insights—for example, highlighting the role of reconnection as a result of flux emergence in heating the low solar atmosphere; confirming the presence of nonthermal particles in coronal nanoflares; identifying resonant absorption and dissipation of Alfvénic waves; and elucidating the mechanisms of thermal nonequilibrium and thermal instability in the corona. Coronal spectroscopy has been performed by the EUV Imaging Spectrometer (EIS) on board Hinode since 2006, providing notable results such as coronal plasma composition and its spatial variation, or the presence of high-velocity coronal upflows and heating in the periphery of (quiescent) active regions, which have been associated with chromospheric spicules and the origin of the slow solar wind. Still, its relatively

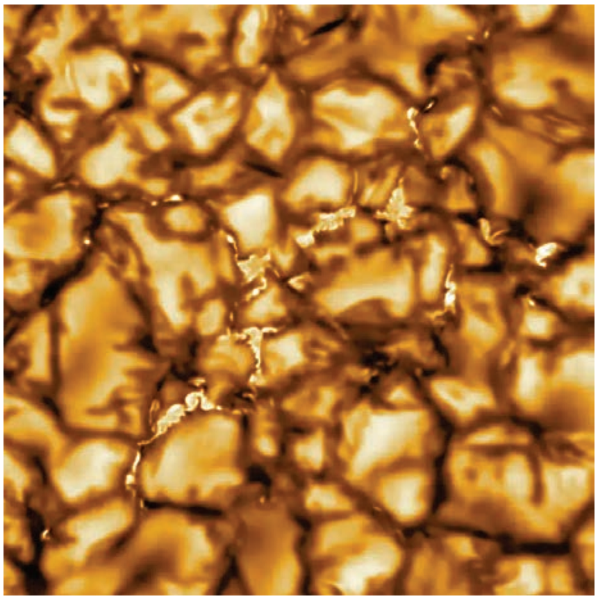

FIGURE B-9 Image of granulation at the solar surface, acquired at 706 nm with the Visible Broadband Imager installed at the 4 m Daniel K. Inouye Solar Telescope. The image covers an 8,200 × 8,200 km (5,000 × 5,000 miles) area on the solar surface. The bright features visible in the intergranular lanes have lateral sizes of 30–50 km at the solar surface and identify footpoints of magnetic flux tubes extending to the corona. Studies of their motions (both transverse and rotational) inform models on the amount and spectral distribution of magneto-convective energy available to coronal heating processes. Note that with a resolution of 100 km or lower, most of these features will be unresolved.
SOURCE: NSO/NSF/AURA, https://nso.edu/telescopes/dkist/first-light-cropped-image. CC BY 4.0.

low cadence (tens of minutes) and coarse spatial resolution (~2,000 km) are now hindering further progress. With their enhanced performances, the EUV coronal spectrograph SPICE on SO, as well as the upcoming MUSE and EUVST missions, will make headway toward resolving the sources of energy flow into the corona.

An even larger step toward resolution would include the combination of soft X-ray (SXR) and hard X-ray (HXR) imaging and spectroscopy, because these regimes contain key diagnostic wavelengths for disambiguating between coronal heating mechanisms—namely, wave versus impulsive (e.g., nanoflare) heating. Heretofore, the technologies needed to make such measurements have been out of reach owing to sensitive fabrication tolerances and lack of analysis techniques; however, pioneering instruments and analysis tools have finally become available, thanks to the NASA sounding rocket and CubeSat programs, which can spectrally probe active region loop heating. Owing to the complexity and breadth of coronal temperature distributions (many orders of magnitude in brightness across more than an order of magnitude in temperature), the greatest advances in understanding the impulsivity of coronal heating will come from combining EUV with both SXR and HXR measurements in an optimized, consistent, and systematic way. In addition to these thermal diagnostics, nonthermal particles produced by extremely small reconnection events (i.e., nanoflares) have been regarded as one outstanding driver for coronal heating. Although their presence has been suggested by HXR observations of their more energetic counterparts by the NuSTAR and the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), ubiquitous UV transient brightenings observed by IRIS, and, more recently, in situ measurements made by PSP, direct observations of the nonthermal signatures have been elusive. Measurements of nonthermal electrons, as diagnosed via sensitive HXR and radio imaging spectroscopy observations, would strongly constrain the energy input and impulsivity of coronal heating.

The continuous coverage of SDO instruments has been a vital asset for most solar, heliospheric, and space weather studies in the past decade; notably, maps of photospheric and chromospheric intensities from HMI and

AIA are necessary to accurately identify the position and context of high-resolution, small, fields-of-view observations (such as those provided by IRIS, Hinode, and Inouye) on the solar disk. The full-disk maps of photospheric magnetic field from SDO/HMI, as well as from NSF's GONG or Synoptic Optical Long-term Investigations of the Sun (SOLIS) facilities, are routinely used to estimate the magnetic field strength and topology in the corona and the heliosphere. These are necessary to understand the flow of mass and energy that heat and energize the corona, solar wind, and energetic particles.

Despite increasingly realistic assumptions about the forced and nonpotential nature of the photospheric field and other constraints, it has been challenging to critically test the accuracy of these extrapolations. Direct field measurements in the upper solar atmosphere, as well as their use to improve extrapolations, remain a long-term goal for the solar community. Steps in this direction are now being taken, such as high-sensitivity polarimetric measurements in the chromosphere (using Fabry-Perot systems like DST/Interferometric Bidimensional Spectropolarimeter [IBIS] and SST/CRisp Imaging SpectroPolarimeter [CRISP]; IR spectrographs such as Inouye/Visible Spectro-Polarimeter [ViSP] and GREGOR/GREGOR Infrared Spectrograph [GRIS]; or UV spectrographs like the Chromospheric Layer Spectropolarimeter [CLASP] sounding rocket) that are providing initial results on the full vector chromospheric fields in plage regions. If selected past Phase A, the Chromospheric Magnetism Explorer (CMEx) SMEX mission will be a dedicated facility to diagnose magnetism from the solar photosphere to the transition region. Linear polarization of visible and near-IR coronal lines in off-limb structures has long been utilized by the Coronal Multi-channel Polarimeter (CoMP) coronagraph and its successor UCoMP to infer the direction of the coronal magnetic field for structures as extended as 2 $R_{\odot}$.

Acquiring the coronal field strength, however, requires precise measurements of the Zeeman circular polarization signal, orders of magnitude weaker than the linear one. Currently only Inouye, with its large collecting area, offers the possibility to derive such a quantity at high resolution over active-region-size fields of view, with initial results only now being realized. Other, complementary techniques are also being tested at this moment, including time-distance coronal seismology; magnetically induced transition of EUV lines (magnetic-field-induced transition [MIT], a new diagnostic technique that leverages a peculiar atomic physic configuration of Fe X, giving rise to an additional transition of the 257.26 Å EUV line in the presence of a magnetic field); and microwave observations of gyroresonance and gyro-synchrotron emission from thermal and nonthermal electrons in active regions. A robust effort will be required in the next decade to obtain reliable and consistent estimates of the vector field in the corona using this variety of methods (see also the LRG in Section B.3).

The heliospheric component of the HSO fleet has grown remarkably in the past decade. Recent missions such as PSP and SO enable heliospheric observations in the poorly sampled inner heliosphere, improving the ability to make connections between the coronal and the interplanetary medium, including the solar wind. These missions, along with L1/1 AU missions like the Atmospheric Composition Explorer (ACE), Wind, Deep Space Climate Observatory (DSCOVR), STEREO, Ulysses which explored out to 5.4 AU, New Horizons, and the Voyager spacecraft have given us critical insight into the global structure of the heliosphere and in situ processes that affect particles and magnetic fields in the heliosphere. These heliospheric measurements also provide insight into the influence of the dynamic solar atmosphere on its extension out into the solar system. In particular, the combination of in situ measurements of plasma, waves, energetic particles, and magnetic fields provide information on the state and evolution of the solar wind and inform its connection back to the Sun.

These measurements have mostly been made at a distance of 1 AU, with some planetary missions providing data from other vantage points. Ulysses ended in 2009, ending access to the out-of-ecliptic view of the solar wind, in particular access to the polar regions above the Sun. As discussed in the Section B.2.2 discussion of PSG 2.a, SO will give us a new chance to sample the heliosphere out of the ecliptic (in the later years of the mission, up to 35 degrees) and give us a new vantage point in the inner heliosphere, with complementary instrumentation to PSP. SO provides both remote sensing and in situ observations of solar wind plasma, energetic particles, and processes in the inner heliosphere for the first time from the same platform. PSP provides measurements of the plasma, magnetic field, and energetic particles in the inner heliosphere and into the corona as close as ~9 $R_{\odot}$, but with limited remote sensing instrumentation.

To bridge the gap between in situ and remote sensing measurements of the Sun, instruments like the Wide-Field Imager for Parker Solar Probe (WISPR) and the Heliospheric Imager on SO (SoloHI) provide views of the earliest stages of the solar wind, as plasma erupts and flows out of the corona and merges into the interplanetary medium. These instruments reveal the structure, density, and velocity profiles of flows inside 1 AU. The future PUNCH mission will similarly image the inner heliosphere, along with a complementary coronagraph and student-provided X-ray spectrometer.

The HelioSwarm mission, with a planned launch in 2028, will consist of a constellation of nine spacecraft in a polyhedral configuration, with separations ranging from MHD (3,000 km) to sub-ion (50 km) scales. The goal of this mission is to examine the 3D nature of turbulence in the heliosphere and how it drives the transport of mass, momentum, and energy in the heliosphere and beyond. HelioSwarm's orbit will take it into the solar wind, magnetosphere, and magnetosheath.

Theory, Modeling, and Simulations

Theory and modeling efforts are a vital component of the system-science approach that characterizes PSG 2. First and foremost, models can "fill the gap" of the currently sparse observations of crucial parameters like the coronal magnetic field, which is the building block of all magnetic connectivity studies. Furthermore, they represent a necessary tool to properly interpret spectral signatures formed by a host of physical processes such as magnetic reconnection, waves, and shock dissipation, and so on that contribute to the creation of the highly dynamic outer solar atmosphere.

State-of-the-art, time-dependent, 3D MHD simulations of the solar atmosphere (e.g., Bifrost, Max Planck Institute for Solar System Research/University of Chicago Radiative MHD [MURaM], Radiative MHD Extensive Numerical Solver [RAMENS], Alfven Wave Solar Model [AWSoM], Athena++, and Adaptively Refined MHD Solver [ARMS]) achieve a high degree of realism and are starting to emulate many observed phenomena, including surface magneto-convection, chromospheric fine structure, and even the emergence process of flare-productive active regions leading to coronal flaring signatures and CMEs. Thanks to the increasing level of computational power, simulations are now starting to explore the effects of important nonidealized processes such as radiative scattering or nonequilibrium hydrogen and helium ionization (Figure B-10). Future developments will also need to move beyond the single-fluid approximation of MHD and consider the effects of multifluid approximation interactions to properly understand the partially ionized chromosphere, a crucial interface region responsible for many coronal properties, such as the observed abundance variations between open and closed field structures. A goal within the next decade is that of physically coupling such models of the solar atmosphere to those of the solar interior (see Section B.2.1), to reproduce the whole process of magnetic field generation, transport and emergence at the surface, and the consequent shaping of the solar atmosphere.

Together with these ab initio models, an important line of research now involves data-driven models of the solar coronal magnetic field and its evolution, such as the Coronal Global Evolutionary Model (CGEM). These models incorporate observed, time-dependent boundary conditions (e.g., the vector magnetic field maps from SDO/HMI) and use various techniques to derive electric fields or plasma velocities necessary to infer the field at different heights. Of particular note is the recent use of neural-network techniques to estimate the all-important surface transverse flows, particularly difficult to measure via direct observations. How to properly incorporate the increasing number of multiheight observations (all obtained at different cadences and resolution) in the models remains an active subject of research.

A proper comparison of the models with the real physical conditions in the solar atmosphere requires reliable and accurate inversions of observed spectro-polarimetric diagnostics. Most of the current techniques use relatively coarse assumptions, including one-dimensional (1D), spatially independent atmospheres, hydrostatic equilibrium, without any reference to nonequilibrium, self-consistent physical processes. A concerted effort is now required to improve these techniques, including a better theoretical understanding of 3D radiative transfer deviations from high-energy, time dependent, nonlocal thermodynamic equilibrium hydrogen ionization. Given the enormous volume of data provided by current telescopes, as well as the high computational costs of spectral inversions, efficient exploitation of computing resources is necessary, and efforts are under way to understand how machine learning approaches can accelerate the process. The complementary approach of forward-modeling the spectral observables in the realistic model atmospheres is also of large value, because it facilitates determining

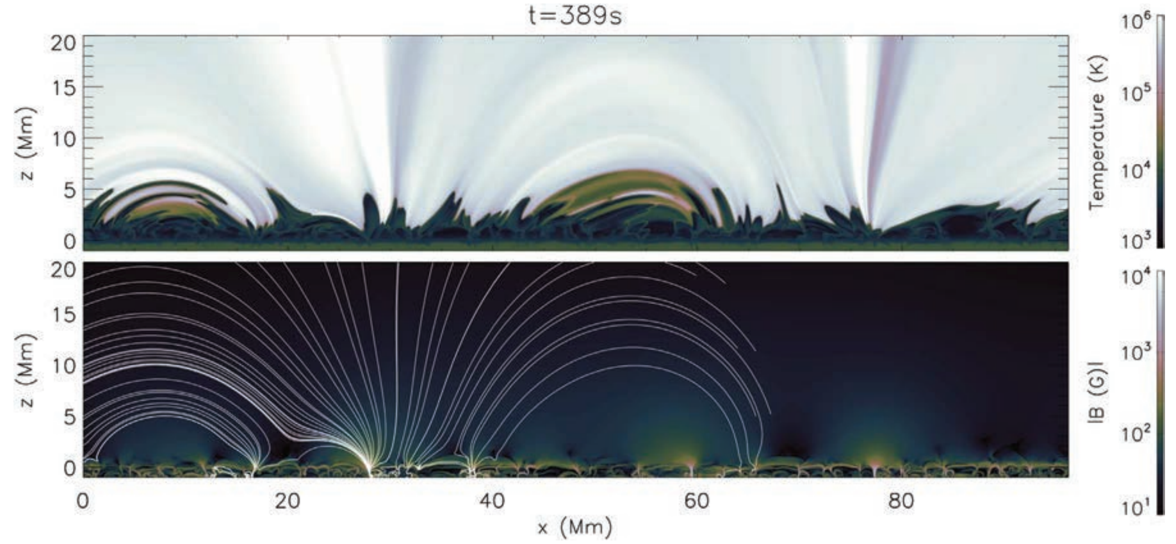

FIGURE B-10 The figure shows the results of a recent simulation with the Bifrost 2.5D radiative magnetohydrodynamic code, including the effects of nonequilibrium ionization (for H and He) as well as ion-neutral interactions. Both mechanisms have profound effects on the resulting structure of the solar chromosphere. Depicted is a slice (x-z) of the simulated solar atmosphere, displaying the temperature (top) and magnetic field configuration (bottom) for a bipolar region. The area covered is 80,000 km in the horizontal (surface) direction, and 20,000 km in the vertical (above the surface) direction. Such numerical simulations provide highly complementary information to direct observations, which can be difficult to properly interpret in complex "interface" regions such as the chromosphere and transition region.
SOURCE: J. Martinez-Sykora, J. Leenaarts, B. De Pontieu, D. Nóbrega-Siverio, V.H. Hansteen, M. Carlsson, and M. Szydlarski, 2020, "Ion–Neutral Interactions and Nonequilibrium Ionization in the Solar Chromosphere," *Astrophysical Journal* 889(2):95, https://doi.org/10.3847/1538-4357/ab643f. © AAS. Reproduced with permission.

the sensitivity of different observables to specific physical conditions in the source atmosphere and, in turn, the identification of missing physics in the models.

Models of the solar corona, when paired with heliospheric models, can provide the best opportunities to map heliospheric plasma and structures back to the Sun; however, even these suffer significant ambiguity into how the magnetic field above the Alfvén surface (the region beyond which most disturbances in the solar wind are unable to propagate back to the photosphere) connects down into specific magnetic structures on the surface. Models like the S-Web, Wang-Sheeley-Arge (WSA), and Space Weather Modeling Framework/AWSOM have made significant advances in more accurately describing the connections between the Sun and the solar wind and heliosphere, but still suffer from incomplete treatment and understanding of physical processes in the corona and heliosphere. For example, the lack of observations of the polar coronal fields significantly impact the ability of these models to correctly specify polar fields and thus realistically model the connections at high latitude. Work is ongoing to connect remote observations of the Sun with heliospheric observations, with models that extend from the solar corona out into the heliosphere, providing a framework for connecting these two regions. Where available, observations can be leveraged to constrain these models both at the Sun and also in the heliosphere. The models inform the understanding of the physics and connections, but ambiguity and difficulty still persist in truly making direct connections between the models and data.

In addition to MHD models describing the interplay between the magnetic field and plasma, kinetic models and models of particle acceleration and transport are key to understanding solar and heliospheric processes and their interconnection. In particular, processes like magnetic reconnection, turbulence, and wave-particle interactions must be treated with kinetic simulations. Models of particle acceleration and turbulent reconnection include

Particle in Cell (PIC) simulations and Vlasov simulations, which can be computationally expensive and do not make predictions on temporal and spatial scales that are observable with remote sensing techniques. Some of these simulation techniques may benefit from advanced algorithms, including machine learning and advanced graphics processing unit–accelerated codes. Further integrating kinetic simulations with MHD models into hybrid models will be key to improving descriptions of the heliosphere.

Solar and heliospheric models have also been extended to other star/planetary systems. As more and more exoplanets are identified around host stars, the question of the influence of their local space environment on their habitability needs to be addressed (see Section B.4.1). Initial work with MHD models has been extended to other astrospheres. This work continues and can be augmented with increased complexity into the next decade. There is a clear need for interdisciplinary work between the astrophysics community and the solar and heliophysics community in terms of collaborative model development and implementation.

Motivation for the Goal

The past decade has witnessed impressive advances in observational and modeling capabilities of the quiescent solar atmosphere and wind. Many of the novel results have further cemented the concept that small-scale phenomena play a fundamental role in creating and structuring the outer atmosphere. Modern facilities like the GST, Inouye, or SO are now available to study in great detail the photospheric flows and magnetic fields that are the ultimate source of the energy necessary for the existence of a corona and wind. However, substantial progress will require a consistent, system-wide approach where these "photospheric inputs" can be causally connected with the properties of the outer atmosphere.

PSG 2 details multiple areas where new development is needed to further advance knowledge of this highly interconnected system. These include high-resolution coronal imaging and spectroscopy to uncover the fundamental characteristics of heating processes; next-generation, highly sensitive radio and HXR instruments to provide unambiguous diagnostics of nonthermal particles in the corona; and remote sensing and in situ observations of solar wind plasma, energetic particles, and processes in the inner heliosphere from multiple vantages around the Sun. Direct observations of the polar magnetic fields and wind properties ultimately will be needed to properly model the magnetic connectivity at high heliospheric latitudes. Most importantly, major efforts will need to be devoted to obtaining reliable, direct measurements of the strength and topology of the magnetic field in the chromosphere and corona, which critically modulates the flow of energy and mass in the whole atmosphere and heliosphere.

System-Level Science Contributions

Making connections between the phenomena observed in the heliosphere and their solar sources is challenging as the plasma originates in the corona where dynamic processes drive the evolution and connections of the coronal magnetic field on timescales of minutes to hours. After radially expanding, the rotation of the Sun creates a magnetic field that can be approximated by the Parker spiral, but evidence from SEP acceleration and transport in the heliosphere across wide longitudinal ranges indicates that the connections back to the Sun do not always follow a simple Parker spiral. These deviations observed in the propagation of SEPs may depend on the background solar wind structure and cross-field diffusion of particles.

Observations of SEPs reveal important insights into physical processes occurring both at their source as well as those influencing their propagation to where they are observed. In the heliosphere, local processes such as acceleration at shocks, plasma compressions, and magnetic reconnection modify the energy of particles, while propagation within plasma turbulence leads to particle scattering and diffusion, and within large-scale structures and current sheets, there are also drift motions. Understanding these processes reveals the nature of the heliospheric magnetic field. The existence of quiet-time high-energy tails on solar wind velocity distributions suggests a persistent stochastic acceleration process occurring in the solar wind in the heliosphere, likely related to turbulence, and which may become more important in the outer heliosphere. Relating SEP characteristics to their solar sources is an area of active research, but this is largely unexplored in the polar regions of the heliosphere. In the energy range between high-energy SEPs and low-energy thermal particles are suprathermal particles whose physics is presumably affected by small-scale kinetic processes. Missions that study local kinetic processes are necessary to improve the understanding of particle acceleration and transport at shocks and in quiet solar wind. The upcoming HelioSwarm and Interstellar Mapping and Acceleration Probe (IMAP) missions are expected to provide significant new observations, complementing those of PSP and SO.

Solar wind heavy ion and elemental composition measures are vital tools for tracing heliospheric plasma back to coronal and chromospheric sources at the Sun. These observational tools are critical to understanding the heating, energization, density structures, dynamic processes, and elemental fractionation in the solar atmosphere. Heavy ion composition also serves as an invaluable tool to identify and classify different sources of plasma (e.g., the interstellar medium, comets, planetary atmospheres) throughout the heliosphere. Inclusion of heavy ion composition measurements on future missions will be critical in supporting connectivity science.

Reconnection is a fundamental process throughout the heliosphere, from the Sun to the outer reaches. Close to the Sun, in addition to driving larger explosive events, reconnection may serve to heat the corona and transport open magnetic flux via interchange reconnection between open fields and closed magnetic fields in large coronal loops. Evidence for the presence of ubiquitous small-scale magnetic reconnection events is thought to exist in the prevalence of switchbacks in the interplanetary magnetic field and energetic particles observed by PSP. Reconnection in the heliosphere can modify the topology of the global heliospheric magnetic field, eroding the magnetic flux added from CMEs. Reconnection exhausts observed in the heliosphere have been shown to be statistically associated with MHD turbulence–driven magnetic field fluctuations. Remote sensing observations of small-scale reconnection events provide crucial input on the energy balance and transport of the solar corona and heliosphere. Meanwhile, a detailed understanding of physical processes from macroscopic to kinetic scales (i.e., down to size scales smaller than the ion gyroradius) through in situ observations and modeling is necessary to further advance studies of phenomena such as magnetic reconnection, turbulence, and collisionless shocks.

B.2.3 Priority Science Goal 3

Solar explosions are the most energetic phenomena in the solar system. Thanks to their proximity, they serve as an excellent laboratory to study fundamental physical processes, including magnetic reconnection, particle acceleration, plasma heating, and shock waves. Meanwhile, large solar eruptive events are the most important drivers for space weather. They affect the entire heliosphere, including, most critically, the near-Earth and deep space environment where humans live and work or where they may someday hope to travel. This science goal also has extensive ties to astrophysical contexts outside the solar system, as questions of how particles are accelerated and how plasma is energized and ejected are ubiquitous across diverse astrophysical phenomena. Furthermore, the explosive release of energy is fundamental to understanding the habitability of stellar systems besides our own and provides signatures that can be studied in other systems.

PSG 3 (Table B-3) captures the community need to understand the origin of solar explosions and how they unleash their energy throughout the heliosphere. This goal is an outstanding, and pressing, motivation of the next decade.

TABLE B-3 Sun and Heliosphere Priority Science Goal (PSG) 3 and Objectives

PSG 3 (of 4)	Objectives
How do solar explosions *unleash* their energy throughout the heliosphere?	a. Determine how and where magnetic energy is stored and suddenly released, from kinetic to global scales, to drive solar transient events. b. Understand the dominant fundamental energy conversion and transportation mechanisms that energize plasma and particles throughout the heliosphere. c. Measure and track the rapidly evolving properties of solar eruptions from the solar surface through interplanetary space. d. Improve methods for forecasting and nowcasting solar eruptions at the Sun as well as the subsequent impacts on interplanetary radiation environments.

Current Research Activity

Priority Science Goal, Objective 3.a

The first objective of PSG 3 addresses the origin and initiation of solar explosions from small to large scales. Achieving progress will require comprehensive knowledge of the vector magnetic field in the photosphere, chromosphere, and corona, as well as diverse and detailed measurements of the plasma environment. The latter includes temperatures, densities, and velocity distributions of all relevant particle species, both before and after magnetic energy release has occurred.

Priority Science Goal, Objective 3.b

The sudden release of magnetic energy in solar explosions is rapidly converted into other forms of energy and quickly transported to both the lower solar atmosphere and interplanetary space. A significant portion of the released energy is contained in energetic particles and heated plasma. However, the detailed physical mechanisms underlying the energy release and transport processes remain poorly understood. To make substantial progress in the next decade, a quantitative determination of the energetic electron and ion distribution over a wide region is required—from the initiation of the solar explosions to their evolution in the upper solar corona and heliosphere—with sufficient spatial, temporal, and spectral resolution.

Priority Science Goal, Objective 3.c

When a solar eruption occurs, a large amount of coronal mass is often ejected into interplanetary space as a CME. Large solar eruptions affect the entire heliosphere and are key drivers of space weather. Therefore, it is critical to characterize their temporally and spatially evolving properties, including magnetic field, momentum, energy, and composition, from the solar surface through interplanetary space. In addition, fast CMEs are often accompanied by shock waves, which are believed to be the main accelerators for SEPs—one of the main concerns for space operations and astronaut safety. Measuring the shock waves and the associated SEP acceleration processes are of profound interest in both fundamental research and space weather applications.

Priority Science Goal, Objective 3.d

Mitigating the impacts of the most extreme space weather events driven by large solar eruptions relies on the ability to accurately predict solar eruptions in advance. Despite progress in the past decade, such a capability is still out of reach and still lies mostly in the domain of basic research. This effort ties closely to the understanding of the fundamental physics at work in magnetic energy release; for example, the use of hot precursor emission to signal the start of a large flare depends critically on understanding the mechanisms by which such hot plasma is released. Similarly, reliable forecasting and nowcasting could tremendously increase the scientific return from science missions by enabling optimal choices of observing plans and by providing flare triggers.

Observational Resources

The past decade has seen rapid development of multiwavelength imaging spectroscopy remote sensing observations and new in situ measurements from different helio-longitudes and distances. These advances have greatly enhanced the capability of constraining the vector magnetic field in the solar atmosphere, the thermal environment in the corona, and the sources and distribution of solar plasma, energetic particles, shocks, waves, and turbulence; all are key measurements in order to advance understanding of the magnetic energy storage, sudden release, and subsequent energy conversion underlying the explosive phenomena on the Sun. Table B-5 (shown later in the chapter) summarizes the mapping between the objectives of PSG 3 and these key measurements.

Most knowledge of solar magnetic fields pre- and post-eruption currently comes from photospheric vector magnetograms, such as those currently supplied by SDO/HMI, which have been playing a vital role in providing high-resolution, high-quality data for more than a full solar cycle. Additional instruments that can perform such vector magnetogram measurements on smaller fields of view include Hinode/SOT, BBSO/GST, DST, Inouye, and a handful of other international instruments. To obtain the magnetic field in the corona where the primary energy release occurs, extrapolations are often performed using the photospheric vector magnetograms as the bottom boundary. While these extrapolations have been useful, they do not replace the value of actual measurements of the coronal magnetic field. Over the past decade, novel instruments at multiple wavelengths have started to offer new knowledge of the coronal magnetic field. EOVSA has demonstrated, for the first time, the ability to constrain the time-varying coronal magnetic field during eruptive flares via microwave imaging spectroscopy observations of gyrosynchrotron radiation. It has also allowed the magnetic field distribution along a reconnection current sheet to be derived, which agrees very well with predictions based on the standard eruptive flare model (see Figure B-3). At optical/IR wavelengths, Inouye now offers the possibility to measure the coronal magnetic field for a small field of view via high-resolution, high-sensitivity imaging spectropolarimetry. The CoMP instrument, a small optical coronagraph, also provides measurements of the linear polarization to infer the direction of the coronal magnetic fields.

During flares and eruptions, magnetic reconnection plays a central role in releasing stored energy. Studying the plasma environment and signatures of reconnection requires detailed knowledge of the plasma at and near the reconnection site, as well as throughout the resulting flare. Observationally, multiband, high-angular-resolution, and high-cadence full-disk EUV observations from SDO/AIA have provided an unprecedented view of the multithermal plasma frozen in the prereconnection and freshly reconnected magnetic flux tubes. Additional instruments that have provided important insights at optical, EUV, and X-ray wavelengths include BBSO/GST, SO/EUI, Hinode/XRT, and, more recently, Inouye. Moreover, instruments that employ slit EUV and UV spectroscopy, such as Hinode/EIS and IRIS, have provided additional diagnostics of the plasma density, temperature, and velocity in the close vicinity of the reconnection site. EUVST, MUSE, CMEx, and the EUV CME and Coronal Connectivity Observatory (ECCCO) (the latter two are in Phase A) all work in the near- to extreme UV regime, with a planned/potential launch later in this solar cycle and promise to make significant advances in this regard with a higher angular resolution, larger field of view, improved imaging spectroscopy capabilities, and better spectral coverage. In situ measurements have also played a vital role. Studies of, for example, magnetic reconnection events in Earth's magnetotail by the Magnetospheric MultiScale (MMS) mission have resolved into kinetic scales of the reconnection processes. And as noted in Section B.2.2, PSP has observed magnetic "switchbacks" and SEPs in the near-Sun solar wind, which may be related to the ubiquitous interchange reconnection events on the solar surface.

Understanding the detailed mechanisms underlying the efficient energization of particles and plasma and the subsequent energy transport requires a quantitative determination of the energetic electron and ion distribution over a wide region—from the initiation of flares/CMEs to their evolution in the upper solar corona and heliosphere—with sufficient spatial, temporal, and spectral resolution. To achieve this goal, multiwavelength remote sensing imaging spectroscopy observations of flares/CMEs at high energies (i.e., radio, EUV, and SXRs), HXRs, and gamma rays) are critical. In situ observations are also key in characterizing the distribution of energetic electrons and ions of different species. For measuring the energetic electrons, in the past 2 decades, there has been transformational progress with the operation of RHESSI from 2002 to 2018, which provided imaging spectroscopy in X-rays and gamma rays and, more recently, SO/Spectrometer Telescope for Imaging X-rays (STIX) in X-rays. For characterizing the multithermal hot plasma heated by flares and eruptions, high-resolution, multiband EUV and SXR imaging observations from, for example, SDO/AIA and Hinode/XRT have played a central role. For instance, the combination of the thermal and nonthermal observations has resulted in a more detailed understanding of phenomena such as quasi-periodic pulsations (QPPs), which may provide a unique diagnostic linking reconnection and particle acceleration with magnetically induced oscillatory behavior at the flaring region (Figure B-11). In addition, EUV, UV, and X-ray spectroscopy observations from Hinode/EIS, IRIS, RHESSI (and upcoming instruments such as MUSE and EUVST) have provided or will provide key diagnostics of the density, temperature, composition, and dynamics of the heated plasma.

At radio wavelengths, thanks to upgraded and new instruments such as the Karl G. Jansky Very Large Array (VLA), the Low Frequency Array (LOFAR), and the Murchison Widefield Array (MWA), researchers have also enjoyed the transition from interferometric imaging at a few discrete frequencies to true radio imaging spectroscopy over broad frequency bands. Exciting progress has been made in diagnosing energetic electrons with radio

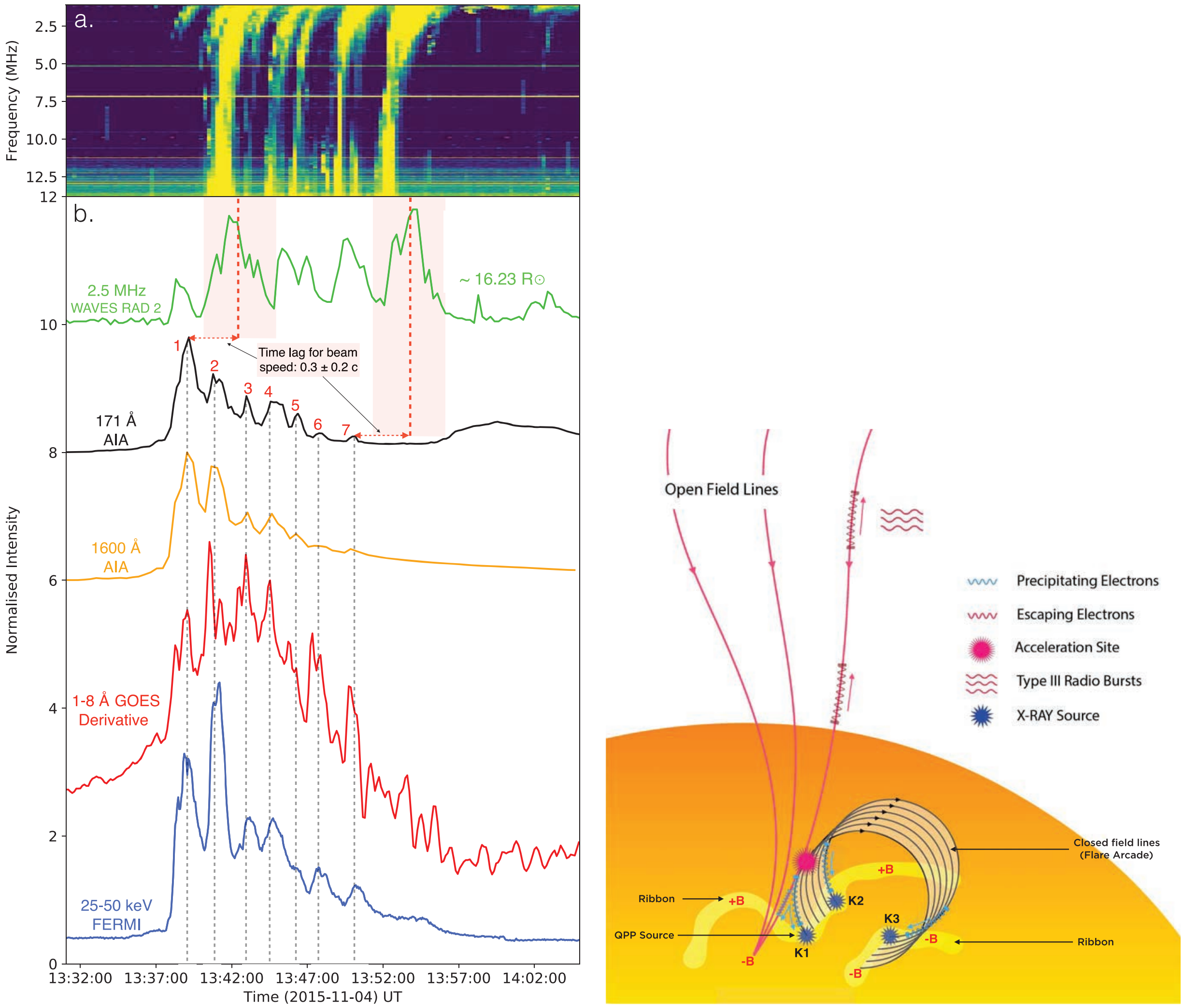

FIGURE B-11 (*Left*) Quasi-periodic pulsations (QPPs), linked to reconnection and particle acceleration in flares, observed at a wide range of wavelengths in a solar flare from November 4, 2015. (*Right*) This illustration highlights that QPPs in flare emission are associated with the entire flaring process and from different emission mechanisms, demonstrating the necessity of high-cadence multiwavelength instrumentation to cohesively probe both thermal plasma and nonthermal particles.
NOTE: AIA, Atmospheric Imaging Assembly; GOES, Geostationary Operational Environmental Satellite.
SOURCE: B.P. Clarke, L.A. Hayes, P.T. Gallagher, S.A. Maloney, and E.P. Carley, 2021, "Quasi-Periodic Particle Acceleration in a Solar Flare," *Astrophysical Journal* 910(2):123, https://doi.org/10.3847/1538-4357/abe463. © AAS. Reproduced with permission.

imaging spectroscopy. In particular, EOVSA has started to offer diagnostics of spatially resolved energetic electron distribution in solar flares with microwave imaging spectroscopy. At longer wavelengths, the Owens Valley Radio Observatory's Long Wavelength Array (OVRO-LWA) is starting to provide daily imaging spectroscopy observations of various solar radio bursts in the middle corona generated by energetic electrons. In space, the Sun Radio Interferometer Space Experiment (SunRISE) Mission, currently set to launch in 2025, will observe radio bursts at even longer wavelengths inaccessible from the ground in an effort to study electron acceleration and transport processes in the upper corona.

Meanwhile, in situ observations of energetic electrons made by instruments onboard Wind, ACE, STEREO, PSP, and SO provide complementary information on energetic electrons that manage to escape to the interplanetary space. Comparisons of the energetic electron population derived from remote sensing and in situ observations have sometimes yielded rather surprising results. For example, only <1 percent of the total number of energetic electrons have been found to escape into interplanetary space in a number of solar flares/jets associated with impulsive in situ energetic electron events.

For energetic ions, unlike their electron counterpart, much of the diagnostics have relied on in situ observations. PSP and SO, in conjunction with Wind, ACE, and STEREO, have opened a new window to study suprathermal and energetic particles from different heliocentric distances, longitudes, and latitudes. For remote sensing techniques aimed at diagnosing energetic ions near the Sun, gamma-ray observations are the primary method. RHESSI had coverage in the gamma-ray regime; however, it lacked the sensitivity to provide routine imaging spectroscopy for gamma-ray sources in flares. In one event, energetic ion footpoints were imaged by RHESSI through their nuclear gamma-ray line emission. They were found to be located in the vicinity of, but not coinciding with, their energetic electron counterpart, offering crucial insights into the ion acceleration processes. More recently, the Fermi Large Area Telescope (LAT) has offered surprising detections of gamma-ray sources associated with behind-the-limb flares, which have been interpreted as precipitated energetic ions originating from the widespread shock front.

Solar eruptions are one of the most important drivers of space weather. In the past decade, substantial progress in tracking the timing, kinematics, and morphology of solar eruptions has been made by using white-light coronagraph images from SOHO/LASCO, STEREO/COR, STEREO/HI, and Coronal Solar Magnetism Observatory (COSMO) K-Cor, as well as multiband EUV images from SDO/AIA, STEREO/EUVI, Geostationary Operational Environmental Satellite (GOES)-R/Solar Ultraviolet Imager (SUVI), and SO's EUI. At the solar surface, instruments such as BBSO/GST, Inouye, and the future MUSE and EUVST have also provided or will soon provide important insights into the initiation process of solar eruptions with extremely high angular resolution and time cadence, despite having a limited field of view. More recently, PSP and SO have provided unprecedented images of solar eruptions close to the Sun through their white-light coronagraphs (Figure B-12). Radio imaging spectroscopy observations of type II radio bursts made by LOFAR have started to reveal the location and evolution of CME-driven shocks

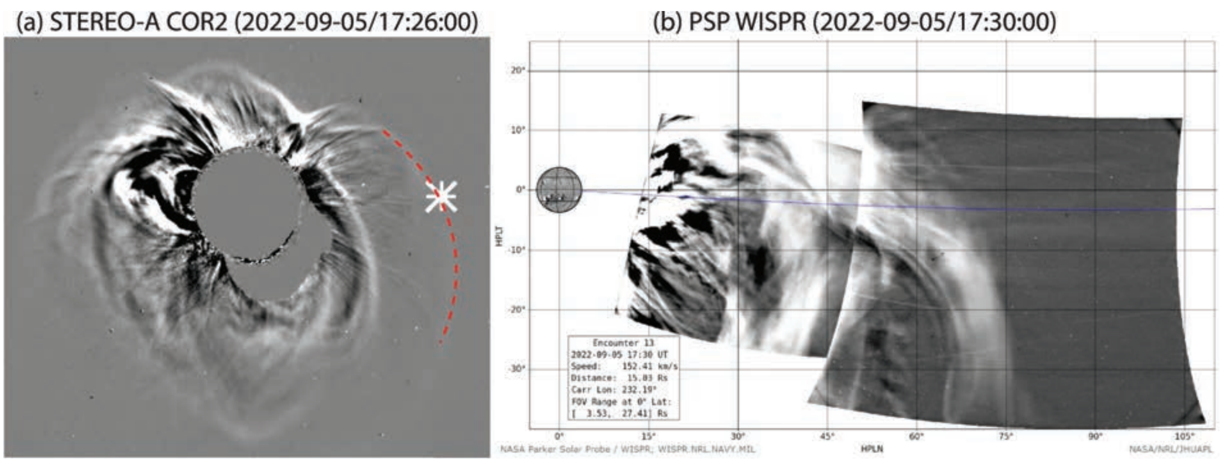

FIGURE B-12 Remote sensing observations of a coronal mass ejection (CME) on September 5, 2022, when the Parker Solar Probe (PSP) encountered a fast-forward shock. An expanding front is evident in the STEREO white-light coronagraph image in the left panel (red line), which swept across PSP (the location of the spacecraft is represented by the white asterisk). PSP provided a close look at the CME front with its white-light coronagraph WISPR (right panel). Combined with its in situ instrument suite, these observations offer an unprecedented view of the highly complex structure in the erupting magnetic flux rope.
NOTE: STEREO, Solar Terrestrial Relations Observatory; WISPR, Wide-Field Imager for Parker Solar Probe.
SOURCE: Romeo et al. (2023), https://doi.org/10.3847/1538-4357/ace62e. CC BY 4.0.

and their associated energetic electrons. In a few cases, faint gyrosynchrotron radiation from the erupting CMEs themselves has been observed by MWA in meter waves, offering a new tool to constrain the magnetic fields and energetic electrons entrained with CMEs. The recent commission of OVRO-LWA will greatly advance such studies with its large number of antennas for interferometry and solar-dedicated observing backends. With a wide-field EUV imager and spectrograph, ECCCO (if selected past Phase A) will track and characterize CMEs in the middle corona range (~1.5–3 solar radii). In addition, PUNCH will soon provide imaging of the CMEs at larger distances (~6–180 solar radii) with its four spacecraft equipped with one white-light coronagraph and three heliospheric imagers.

In interplanetary space, in situ observations made by PSP, SO, STEREO, and other near-Earth instruments (e.g., Wind, ACE) have provided detailed measurements of the magnetic field, thermal structure, energetic particle distributions, and elemental abundances of interplanetary CMEs (or ICMEs) as they arrive at the spacecraft. These in situ studies not only constrain the thermal history and energetics of CME release but also allow us to trace heliospheric plasma back to its sources at the Sun. For example, low-charge heavy ions have been observed to be associated with prominence eruptions, serving as a useful tool for tracing the evolution of structures from the Sun out into the heliosphere.

Theory, Modeling, and Simulations

Theory, modeling, and simulations are vitally important for addressing the variety of science topics related to PSG 3. Combined with the multifaceted remote sensing and in situ observations described above, solar explosive events serve as an ideal laboratory for carrying out such theoretical and modeling studies. However, because the spatial scales of the fundamental processes underlying solar explosive events, which include magnetic reconnection, particle acceleration/transport, shocks, waves, and turbulence and span many orders of magnitude all the way from kinetic scales (a few tens of meters) to global scales (the size of a solar active region to the entire solar system), there are significant challenges in developing comprehensive codes and tools to faithfully model these processes.

In the past decade, exciting progress has been made in developing sophisticated MHD models with state-of-the-art codes and ever-increasing computing power. In particular, recent, large 3D MHD simulations have yielded a high degree of realism for reproducing certain observed phenomena in solar flares. Some results of recent studies have led to new insights that may have reshaped understanding—for example, a recent study uses synthetic observations derived from 3D resistive MHD simulations to demonstrate through modeling that "supra-arcade downflows" could result from secondary magneto-fluid instabilities in the turbulent region above the flare arcade. Meanwhile, data-driven MHD simulations based on realistic observational data have also blossomed. Examples include those using the observed, time-dependent photospheric magnetic fields and/or flows to drive the simulations (Figure B-13).

Energetic charged particles carry a significant portion of the total energy released in solar explosive events. They are responsible for producing a variety of bright emissions across the electromagnetic spectrum from the photosphere to the corona (either directly or indirectly). The particles that escaped to interplanetary space, known as SEPs, also have strong space weather implications. However, modeling the acceleration and transport of the charged particles, as well as how they interact with the plasma environment, requires detailed knowledge of the relevant processes down to kinetic scales. Although limited by their small domain size, PIC simulations have provided much insight into these processes. Recently, large 3D PIC simulations have, for the first time, managed to produce power-law spectra for both energetic electrons and ions in 3D low-beta magnetic reconnection systems, which have long been suggested by observations but have not been reproduced by previous PIC simulations.

Significant progress has also been made in macroscopic particle simulations. Some models employ an analytical approach to model energetic electrons in an MHD framework. Other models combine the 1D radiation hydrodynamics model RADYN with Fokker Planck simulations or observational constraints to study the response from the lower atmosphere by particle beams. Recently, efforts have been made to carry out particle acceleration and transport modeling within an MHD skeleton to simulate the time-dependent distribution of energetic particles in a macroscopic domain. An exciting breakthrough in this regard has been made through the "kglobal" model, which marks the first macroscopic simulation of magnetic reconnection that incorporates both MHD and particle processes in a self-consistent manner.

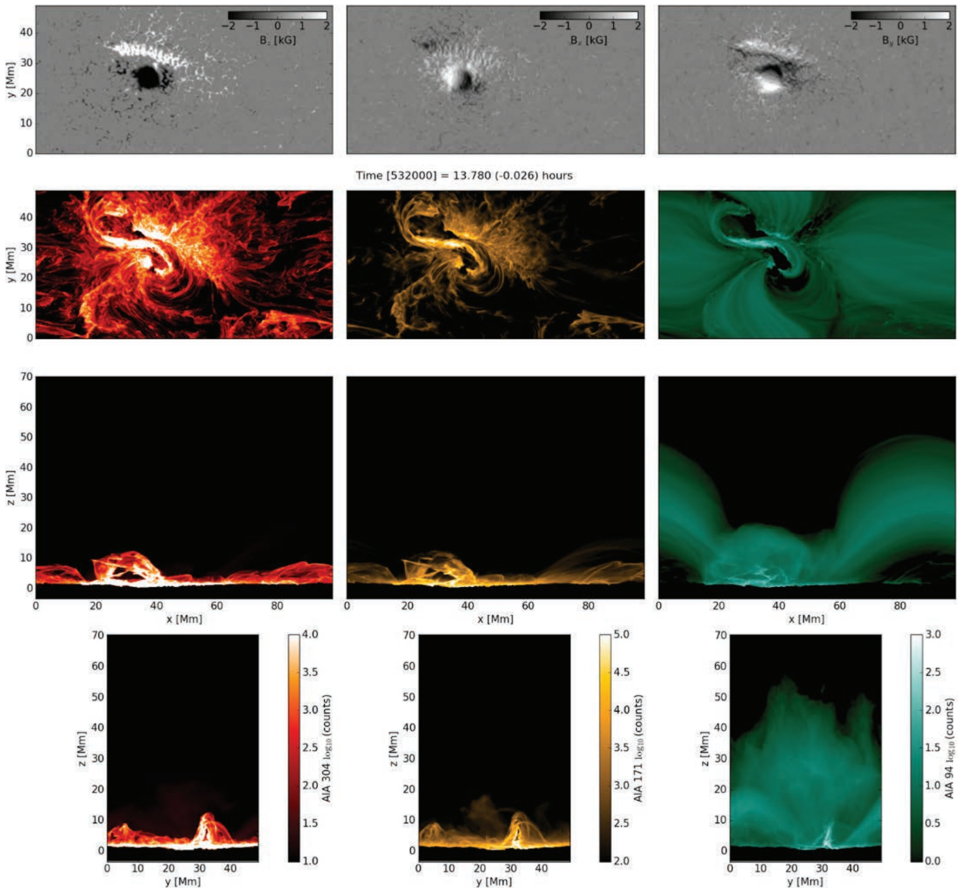

FIGURE B-13 Large three-dimensional magnetohydrodynamic simulations can now reproduce realistic detailed structures in active regions. Shown here is a simulation of a solar active region with an embedded magnetic flux rope that is about to erupt. The top panels represent the three components of the observed photospheric magnetic field (B_z, B_x, B_y). The bottom panels show synthetic extreme ultraviolet emission maps as would be seen by Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) at different channels (from left to right: 304 Å; 171 Å; 94 Å) and two different viewing perspectives (top-down for the second row and edge-on for the third row).
SOURCE: Rempel et al. (2023), https://doi.org/10.3847/1538-4357/aced4d. CC BY 4.0.

As for solar eruptions that enter the upper solar corona and interplanetary space, modeling plays a key role in understanding the evolution and dynamics of the erupting material in 3D, as well as predictions for potential space weather threats. Models for reconstructing the 3D CME structures using multiperspective measurements from SOHO and STEREO have been widely used. For numerical simulations that address global scales, leading codes include AWSoM, MHD Algorithm outside a Sphere (MAS), and the heliospheric model WSA. Modeling also plays an important role in reconstructing the characteristics of the magnetic flux ropes using in situ measurements of ICMEs. There have also been efforts to simulate particle acceleration by CME-driven shocks, corotating interaction regions (CIRs), and stream interaction regions (SIRs).

Motivation for the Goal

Understanding the physical processes underlying solar explosive events has been a priority goal for the 2013 solar and space physics decadal survey (NRC 2013; hereafter the "2013 decadal survey"). Despite the substantial progress made, it is still far from being accomplished. In light of the current strategies, PSG 3 targets the areas where new development is needed to make further progress. The "Needed Capabilities" column of Table B-5 (shown later in the chapter) outlines the required capabilities to address each of the four objectives. They are briefly discussed below in the context of existing capabilities.

First, current capabilities in measuring the coronal magnetic field remain limited. At optical/IR wavelengths, owing to its small aperture, CoMP is unable to detect the Stokes V signal needed to measure the coronal magnetic field strength. Although Inouye is poised to make breakthroughs, thanks to its large aperture and high sensitivity, its slit spectrograph and relatively small field of view make it difficult to see the "big picture." Moreover, because the solar disk is millions of times brighter than the coronal signal in optical/IR, the coronagraphs are inherently limited to measurements off the solar limb. While microwave imaging spectroscopy allows coronal magnetic fields to be constrained both against the disk and off limb, EOVSA does not have sufficient dynamic range, imaging fidelity, and resolution to derive detailed coronal magnetic field maps outside strong flare sources and active regions. For magnetic field measurements of solar eruptions and solar wind in the upper corona and interplanetary space, only occasional remote sensing and in situ measurements have been made. Such a lack of capabilities in directly measuring coronal magnetic fields calls for the development of new instruments and methods in multiple wavelengths (described further in the SHP LRG, Section B.3).

For detecting and quantifying energetic electrons from solar explosive events, remote sensing HXR and radio observations have been the primary means. At present, one profound limitation lies in their sensitivity and dynamic range available for imaging spectroscopy. In HXRs, owing to the indirect imaging method that RHESSI employed, the dynamic range was limited to 10:1 or so. As such, the coronal HXR sources, which are of particular interest thanks to their proximity to the presumed particle acceleration site, are usually overpowered by the bright footpoint sources. At radio wavelengths, owing to the small number of antennas, EOVSA has similar limitations in dynamic range. Such a limitation has hampered the ability to trace and quantify the energetic electron distribution over a broader flaring region, which is required to pinpoint the electron acceleration site and disentangle the acceleration and transport processes. Ergo, locating and quantifying energetic ions from the solar surface to interplanetary space has been critically lacking.

Consequently, very little is known about where and how energetic ions are accelerated in solar flares, despite the fact that these ions may contain as much energy as energetic electrons. While Fermi/LAT has provided new insights, it has too coarse of an angular resolution to precisely pinpoint the source location. As such, to make significant progress, a next-generation gamma-ray spectral imager with extremely high sensitivity and improved resolution is required.

For a full understanding of how the Sun ejects the coronal plasma and energizes particles over the entire lifetime of an explosive event, it is necessary to combine multiwavelength remote sensing observations of its source region and spatial-temporal evolution with in situ measurements of the resulting plasma and particles throughout the heliosphere. Such studies not only help to constrain the conditions of particle acceleration and plasma heating, but also elucidate the transport effects experienced by the particles along their journey. Achieving this goal requires not only comprehensive multiwavelength remote sensing observations, but also continued in situ measurements of energetic electrons, ions of multiple species and charge states, and neutral atoms from heliospheric locations that sample as many longitudes and latitudes as possible. Additionally, multispacecraft constellations or networks of space- and ground-based telescopes with complementary instrumentation will be required to reconstruct the 3D structures of CMEs/shocks and to determine the latitudinal and longitudinal extent of energetic particle populations accelerated close to the Sun.

More precise and accurate forecasting of solar explosive events is needed both in order to further explore energy release at the Sun and to mitigate the impacts of energy release on interplanetary radiation environments. An example of the former is that many telescopes have small fields of view and thus miss a lot of flares unless they happen to be pointed in the right location. Accurate predictions of when and where the events are going to occur would allow more telescopes to better capture the events, which is especially important during the multimessenger era of observations. Investigations of flare and CME forecasting for space weather purposes need to be closely tied to studies of fundamental physics. For example, studies of magnetic field configurations that are likely to erupt might eventually lead to the prediction of eruption direction and angular extent as well as whether an eruption will have a southward-directed magnetic field when it arrives at Earth (a crucial parameter for assessing geoeffectiveness). The accurate prediction and understanding of CMEs impacting Earth's magnetosphere is not the only need. As society prepares for the advent of interplanetary human travel and the return of astronauts to the Moon, a much more thorough understanding of how solar activity affects radiation environments will be required. Certainly, for environments outside the terrestrial magnetosphere, a large amount of advance warning could significantly lower risks to humans and technology.

To improve the forecasting and nowcasting of solar explosive events and to accurately predict their effects on interplanetary radiation environments, significant work on observations and modeling is needed. Flare forecasting requires not only observationally constrained vector magnetogram information (discussed above), but also modeling that can elucidate the locations and quantity of magnetic stress buildup. In addition, forecasting and nowcasting require measurements of early emission signatures, such as radio and HXRs (which come from accelerated particles produced early in the event), EUV/UV/H-α signatures that indicate energy deposition to the lower atmosphere, SXRs to provide a rough estimate of the total energy released in an event, as well as in situ measurements of highly energetic particles that arrive at the spacecraft at nearly the speed of light. A key aspect of all these instruments is that the data and modeling output need to be available in near real time in order to be useful for near-term forecasting and nowcasting.

System-Level Science Contributions

The study of solar explosive events spans essentially all regions of the solar system—from flux emergence in the solar interior, to energy release in the solar corona, to their propagation and evolution in the heliosphere, and to their impacts on Earth's and other planetary systems' magnetospheres and lower atmospheres. Therefore, understanding the origin and the associated physical processes of solar explosive events constitutes one of the most important contributions to system-level science for solar and space physics.

This science goal makes vital contributions to EO 1 (Section B.4.1), relating solar and stellar activity, which is particularly important as more and more exoplanets have been discovered, some of which are located within the so-called habitable zone. However, the particle and radiation environment around the exoplanets, known as the "exo-space weather" induced by the stellar wind and transient explosive events from their host stars, may drastically change the evolution and habitability of these exoplanets. The study of the exo-space weather is still in its infancy; an improved understanding of exo-space weather relies on advances in unraveling the underlying physics behind the explosive events and their impacts on the planetary systems in our own solar system.

These objectives are also critically linked to EO 2 (see Section B.4.2), which highlights the significant impacts that solar activity has on human deep space travel. As the Artemis and Mars-forward programs ramp up the frequency and duration of humans spending time in unsheltered space environs, it is crucial to have the capacity to understand and predict the radiation environments that astronauts are inhabiting.

B.2.4 Priority Science Goal 4

The outer heliosphere and LISM are largely unexplored frontiers with new discoveries awaiting. Understanding the heliosphere is vital to understand our home in the galaxy. GCRs, a major space weather hazard harmful to humans and that permeate the galaxy, are significantly shielded by the heliosphere. This moderation bears a direct impact on protecting life on Earth. Moreover, study of the heliosphere/LISM interaction cuts across disciplines, because the heliosphere resembles astrospheres that surround other stars (see Table B-4).

The interaction between the Sun and the LISM creates a number of boundaries and a wide diversity in plasma physics processes. The heliosphere itself is a vast region carved out of the LISM by the solar wind (Figure B-14). The supersonic and super-Alfvénic solar wind is heated and slowed at the TS, which was crossed by Voyager 1 and 2 in 2004, and 2008, respectively. Beyond the TS is the HP, a boundary which separates plasma of solar origin with that of interstellar origin. The region between the TS and HP is known as the heliosheath. The plasma of the outer heliosphere contains a variety of species including solar wind ions and electrons, and even neutral solar wind atoms, interstellar neutral atoms, PUIs from both interstellar and solar origin, dust, and cosmic rays,

TABLE B-4 Sun and Heliosphere Priority Science Goal (PSG) 4 and Objectives

PSG 4 (of 4)	Objectives
How is our *home in the galaxy* sustained by the Sun and its interaction with the local interstellar medium (LISM)?	a. Ascertain the physical processes from the Sun to the LISM that shape the heliosphere and determine the spatial and temporal dependence of its boundaries. b. Establish how the dynamics and evolution of the global heliosphere are affected by solar activity, and by the LISM and its inhomogeneities. c. Determine how pickup ions are heated and accelerated across the termination shock, evolve in the heliosheath, and escape across the heliopause into the LISM. d. Infer how and where anomalous cosmic rays are accelerated, and how they and galactic cosmic rays are modulated by the Sun, heliosphere, and LISM.

both of galactic origin (GCRs) and of heliospheric origin (ACRs). Voyager 1 and 2 each crossed the HP in 2012 and 2018, respectively.

Current Research Activity

PSG 4.a

The overall shape of the heliosphere, what physical processes determine the shape, and how it evolves is unknown and under debate, but is an area in which researchers anticipate much progress in the next decade. In the broadest terms, the heliosphere is formed by the balance of the outward pressure of the solar wind with the inward pressure of the LISM. Indeed, a nascent understanding of the shape of the heliosphere has been made with IBEX by correlating temporal variation in ENA observations to variations in the solar wind dynamic pres-

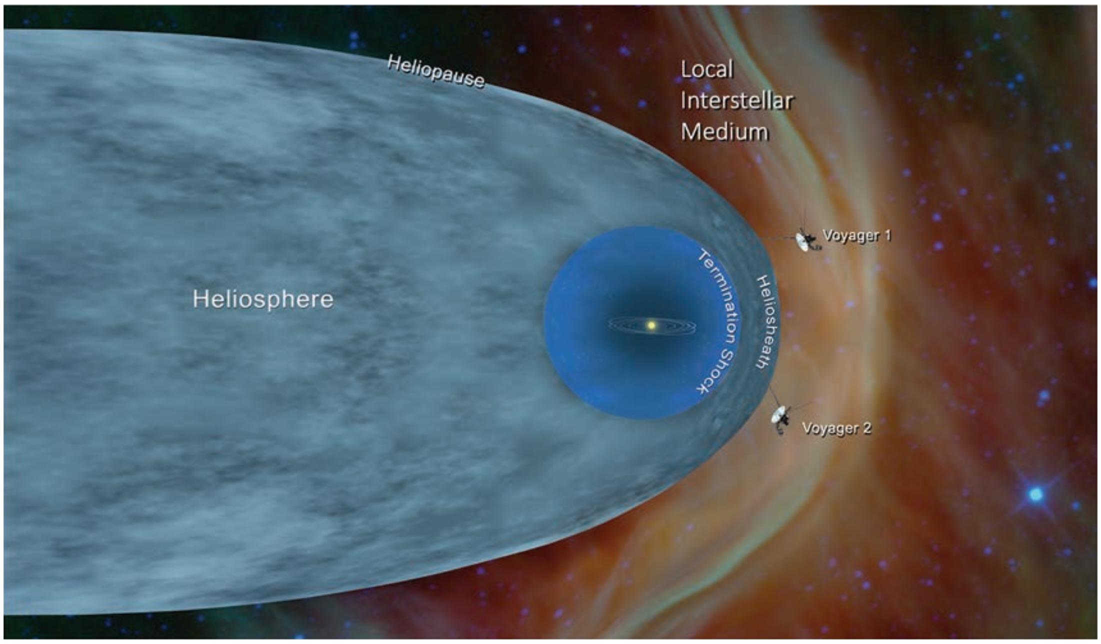

FIGURE B-14 A schematic depiction of the heliosphere. The heliosphere is a plasma bubble, carved out of the local interstellar medium by the solar wind, and marks the edge of the Sun's direct magnetic influence in space. Also shown are the approximate locations of the two Voyager spacecraft, both having crossed the heliopause in the past decade. As of January 2024, Voyager 1 was at a distance of 163 AU from the Sun, and Voyager 2 was at a distance of 136 AU.
SOURCE: NASA/JPL-Caltech.

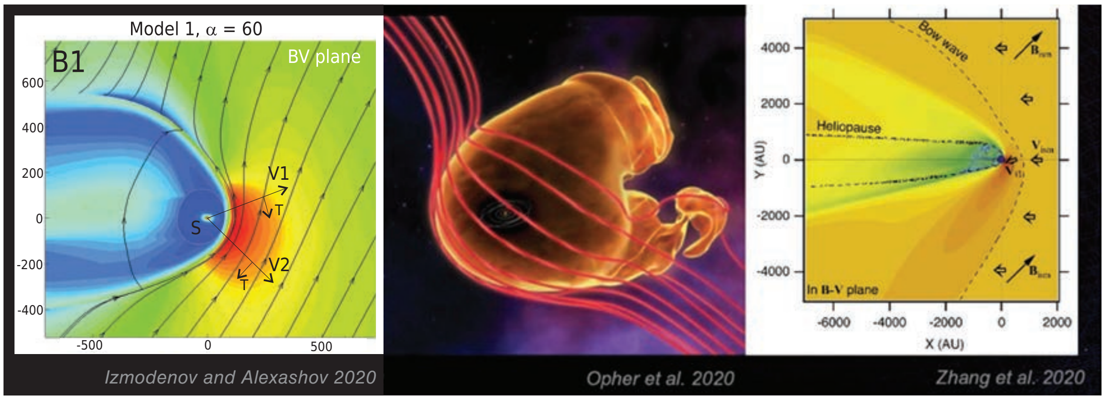

FIGURE B-15 State-of-the-art global models of the heliosphere predict different shapes: a comet-like shape (left model by Izmodenov and Alexashov [2020] and right model by Zhang et al. [2020]) and the "croissant" model (by Opher et al. 2020). SOURCES: (*Left*) Izmodenov and Alexashov (2020), https://doi.org/10.1051/0004-6361/201937058. CC BY 4.0; (*Middle*) M. Opher, A. Loeb, J. Drake, and G. Toth, 2020, "A Small and Round Heliosphere Suggested by Magnetohydrodynamic Modelling of Pick-Up Ions," *Nature Astronomy* 4:675–683, reproduced with permission from SNCSC; (*Right*) M. Zhang, N.V. Pogorelov, Y. Zhang, H.B. Hu, and R. Schlickeiser, 2020, "The Original Anisotropy of TeV Cosmic Rays in the Local Interstellar Medium," *Astrophysical Journal* 889(2):97, https://doi.org/10.3847/1538-4357/ab643c. © AAS. Reproduced with permission.

sure observed in the inner heliosphere, which supports this picture. However, there are many unknowns, such as how the polar extension of the Sun's magnetic field affects the shape of the heliosphere, and how the tail of the heliosphere interacts and mixes with the LISM (Figure B-15). Is it a long and extended comet-like tail, or does the tail break apart into turbulent eddies? Questions also persist regarding the structure of the boundary layers of the heliosphere and how they evolve. What is the nature and structure of the heliopause? What are the physical processes that form the IBEX Ribbon and determine its extent and shape? What is the nature of the hydrogen wall and the bow wave or shock?

Priority Science Goal, Objective 4.b

A major finding from IBEX is that the heliosheath responds rapidly (on timescales of <6 months) to changes in solar wind variation and is thus strongly coupled to the solar cycle. Yet to be resolved is to what degree and how the size of the heliosphere changes over time as well as exactly what physical processes drive its evolution. In addition, there remain puzzles concerning Voyager in situ observations of suprathermal ions and cosmic rays in the heliosheath, particularly whether they are related to solar cycle variations or caused by variations related to their proximity to the heliospheric current sheet in the heliosheath. The changing solar cycle leads to variations in the IMF strength, turbulence, and polarity, which affect transport coefficients, acceleration rates at shocks, and cosmic-ray drift patterns. On longer timescales, the heliosphere is affected by variations in the LISM. The heliosphere is now exiting the Local Interstellar Cloud (LIC) and on its way to the G cloud. Upper limits on interstellar Mg II absorption in the direction of the Sun's motion predict that the heliosphere will leave the LIC in fewer than 1,900 years. A long time to be sure, but it is possible that the heliosphere will intercept smaller scale inhomogeneities in ISM properties in this transition zone. Ultimately, as the heliosphere leaves the LIC, dramatic changes are expected in the size of the heliosphere, the properties of the solar wind, and the composition of the interstellar neutrals.

Priority Science Goal, Objective 4.c

More than any other particle population, understanding the formation, heating, and evolution of PUIs is essential for understanding the physics of how the heliosphere is formed and sustained. PUIs originate when neutral interstellar gas that permeates the heliosphere is ionized and "picked up" by the solar wind as it flows outward. It is important to track the evolution of the PUIs and to determine how the properties of the interstellar neutral source varies throughout the heliosphere. By the time the solar wind reaches the outer heliosphere, PUIs carry the bulk of the thermal energy; and beyond the TS, PUIs dominate the force balance in the heliosheath against the LISM pressure. Heliosheath PUIs that escape beyond the HP may be a secondary source of Ribbon ENAs. How PUIs (and ACRs) transit across the HP will provide important information on the nature of the HP.

Priority Science Goal, Objective 4.d

Where ACRs are accelerated remains an open question. A leading theory is that they originate at the flanks of the heliosphere, but there are other theories, such as acceleration by magnetic reconnection or turbulent plasma compressions in the heliosheath. With regard to GCRs, it is not understood how the heliosheath and HP are so effective at modulating GCR intensity, as was noted by the Voyagers (see Figure B-16). Central to this is understanding how turbulence affects charged-particle transport, which is at the very core of the understanding of GCR modulation throughout the heliosphere.

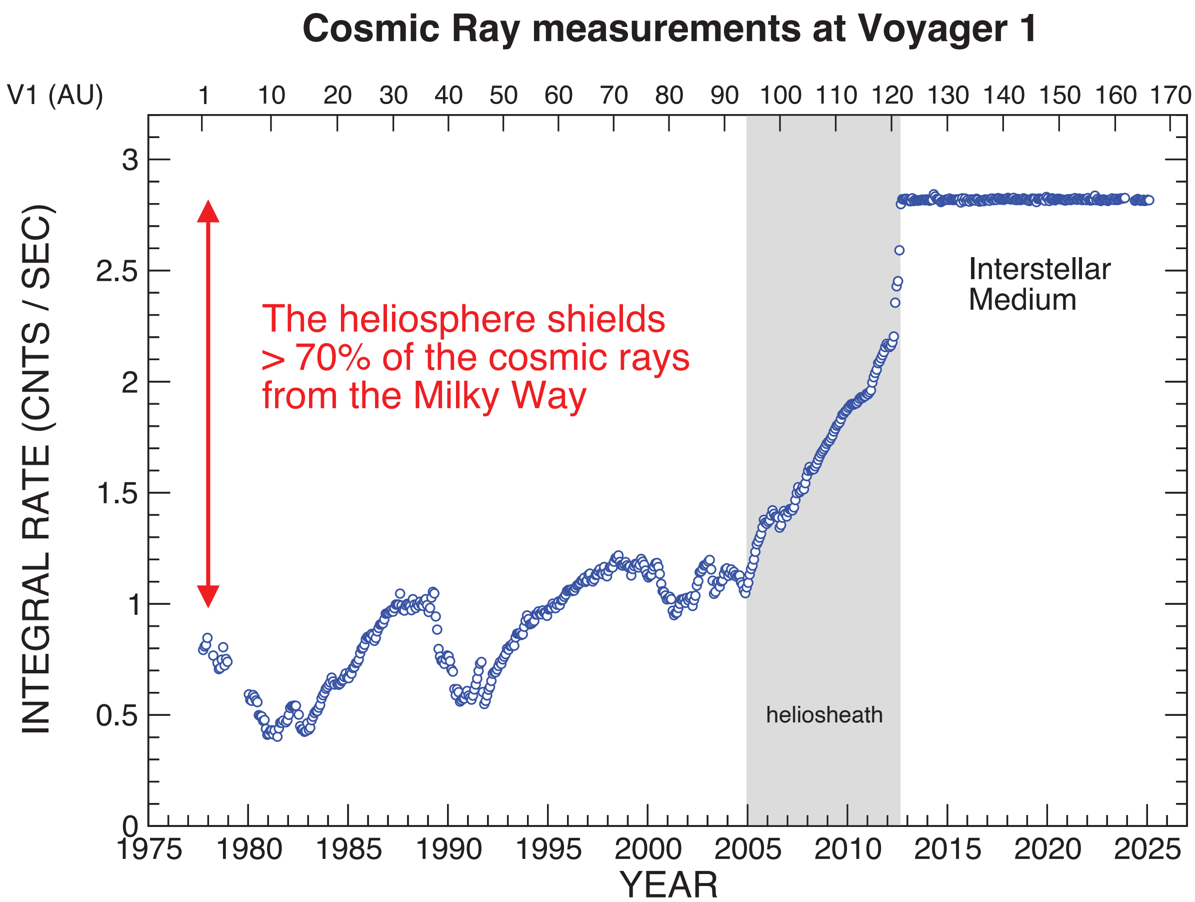

FIGURE B-16 Count rates of >70 MeV (mostly) galactic cosmic ray protons measured by Voyager 1 over the whole mission. Galactic cosmic rays (GCRs) increased significantly in the heliosheath and had a very large jump at the heliopause. This effect shows that GCRs are modulated almost immediately upon entering the heliosphere and represents a challenge to understanding. SOURCE: Opher et al. (2023), https://doi.org/10.3389/fspas.2023.1143909. CC BY 4.0.

In addition to the above research thrusts, the panel notes that the distribution of dust in the heliosphere provides important information about the heliosphere, as well as having broader implications related to understanding the origin of the solar system and the nature of our home in the galaxy. The sources of dust grains vary widely from those produced by planets, moons, comets, asteroids, and meteoroids, and possibly even from outside the heliosphere of interstellar origin, such as from asymptotic branch stars and supernovae explosions. Dust grains are charged by solar UV and interaction with the solar wind. As such, in addition to gravitational and radiation pressure forces, including Poyting-Robertson drag, the paths of dust grains in the solar system are also affected by electric and magnetic fields. The mass-to-charge ratio is a critical parameter, as is the ratio of the radiation pressure force relative to that of gravity. These are largely determined by the size of the dust grains. Thus, understanding the size distribution of dust in the heliosphere will significantly improve the understanding of the origins of dust grains. The distribution and properties of dust are also important probes of the heliospheric structure.

Observational Resources

It is truly remarkable how much has been learned about the nature of the outer heliosphere and LISM from the two venerable Voyager spacecraft and the Earth-orbiting IBEX mission. Observations from these spacecraft have provided rich inputs for the modeling community, leading to sophisticated simulations of the global heliosphere and theoretical insights into particle processes at the TS and beyond.

Currently, the Voyager 1 and 2 spacecraft are returning measurements from the LISM near the heliosphere (sometimes called the very local interstellar medium [VLISM]) on plasma waves, magnetic fields, and cosmic rays. The Voyagers do not store data onboard and only return data during certain times each day. Thus, there are numerous data gaps. The Voyager team has recently implemented a revision of the Voyager operational plan to extend the mission life to perhaps 2040, although diminishing power margins will require the last of the particle instruments to end operation around 2029. Voyager 2 has a functioning plasma instrument to measure density and velocity, but it is not well suited to measure the plasma of the LISM, which is too cold and not moving in the right direction to be easily measured by the instrument that was designed to measure the solar wind.

Both spacecraft measure ions from about 30 keV to more than 100 MeV in a number of directions, and both measure ACRs and GCRs, with three separate telescopes, providing some information on the anisotropy of these particles, which is enhanced further through spacecraft roll maneuvers. This information is particularly important with regards to the question of the source of ACRs, one of the key objectives of PSG 4. There is a gap in the coverage between about 1 keV and 30 keV. This energy range is critical because this is where interstellar PUIs would be most easily observed. In the outer heliosphere, PUIs are the dominant component to the overall pressure of the plasma and are also a significant component to the density. Yet, neither Voyager spacecraft has instrumentation to measure this component of the plasma.

New Horizons, at 58 AU from the Sun (as of January 2024), has instrumentation to measure PUIs. Indeed, it is the only spacecraft to visit the outer heliosphere to have PUI measurement capability, making it an invaluable addition to the HSO. While it is still well inside the radius of the TS, traveling at 3.5 AU/year, it could potentially cross it in the coming decade. The spacecraft also has instrumentation to measure energetic ions and will allow researchers to determine whether the heating and acceleration of PUIs at the TS are the source of low-energy ACRs, at least locally where the spacecraft crosses the shock. A key limitation of New Horizons, however, is the lack of magnetic field measurements.

The IBEX mission provides maps of ENAs that are produced in the outer heliosphere. ENAs are produced when a charged particle attains an electron via charge exchange with preexisting neutral atoms—for example, cold interstellar gas. ENAs reveal the charged-particle environment of the outer heliosphere, but current measurements are limited to line-of-sight integrations—analogous to photon observations of optically thin material—rather than in situ measurements. These maps are extremely useful for inferring properties of the global heliosphere, and the energy distribution of charged particles over a large volume. Using known charge-exchange cross sections, plasma ion distributions can be derived. Most of these particles come from the heliosheath. The Voyagers provide "ground truth" measurements in the ~0.03–1 MeV energy range, which is a higher energy range than the ENA maps produced by IBEX but do provide some comparative information. These maps also help reveal the physics occurring in the VLISM, which is presumably where the source of the IBEX Ribbon is located. The source is likely secondary PUIs, which are created by the charge exchange between energetic neutral solar wind atoms with the ionized component of the LISM gas. These secondary PUIs move under the influence of electric and magnetic fields in the LISM, and their distribution is inferred from observations of the Ribbon.

In the next decade, IMAP will provide considerably more detailed ENA maps, with greater instrument sensitivity, a higher spatial resolution, and a larger energy range. IMAP will provide unprecedented, high-resolution, and broad-energy-range measurements of ENAs coming from the outer heliosphere, creating all-sky ENA maps that track spatial and temporal variations in the structure of the heliosheath, carrying on the work of IBEX. Comparisons of the higher-resolution global ENA maps from IMAP with large-scale MHD modeling of the heliosphere will be capable of determining structure on smaller scales, such as from Rayleigh-Taylor-like instabilities near the HP. The combined higher spatial and energy resolutions will provide the necessary observations to determine the origin of the Ribbon.

IBEX has also continued to make progress in determining the properties of interstellar neutrals, in particular helium, through their direct measurement. Interstellar neutral atoms are an important component of the particle populations in the heliosphere. In fact, neutrals are the dominant species in the outer heliosphere and in the LISM where the medium is only partially ionized. Their influence on fields and plasma, however, occurs on very large scales (several tens of astronomical units) owing to their weak interaction with the ionized component. However, they do play a consequential role in the global structure of the heliosphere. For instance, IBEX measurements of the flow velocity and temperature of interstellar helium have been applied to the question of whether there is a bow shock in the upwind direction of the LISM flow beyond the HP. These measurements, along with determination of the IMF direction derived from the IBEX Ribbon geometry, continue to build the case that there is no bow shock, but rather a bow wave.

In addition to the spacecraft exploring the outer heliosphere, those in the inner heliosphere as part of the HSO, such as ACE and the in situ complement of the IMAP mission, provide important measurements of the solar wind and interplanetary magnetic field, which provide boundary conditions for large-scale models of the heliosphere. In addition, the measurements from these spacecraft allow us to relate the passage of solar structures at 1 AU to those seen in IBEX and IMAP ENA maps. This correlation informs us of the heliosphere's response to the Sun.

Another interesting diagnostic of the heliosphere demonstrated in the past decade is that of the arrival direction of teraelectronvolt-energy cosmic rays at Earth. While the intensity of cosmic rays of this energy are not affected by the heliosphere in the same way as lower-energy galactic cosmic rays (tens of megaelectronvolts to several gigaelectronvolts), the electric and magnetic fields within the heliosphere do influence the motion of these particles. Thus, observations of the anisotropy of teraelectronvolt-energy cosmic rays, combined with large-scale computer modeling of the trajectories of these particles through the heliosphere, can be used to infer global properties of the heliosphere.

Neutron monitors are a valuable resource, providing measurements of the intensity of cosmic rays at the top of Earth's atmosphere. They provide information over a broad range of timescales, such as solar-cycle variations caused by the heliospheric modulation of GCRs. They also measure shorter timescale variations related to transient solar phenomena such as ground-level enhancements, lasting minutes to hours, caused by extremely intense solar proton events, and Forbush-decreases, on scales of days to weeks, caused by the passage of very fast CMEs that reduce the intensity of GCRs. Thus, neutron monitors are important to the understanding of the local space radiation environment and also provide a critical in situ measurement of GCRs that can be compared to models of GCR modulation in the heliosphere.

Earth-based radio telescopes such as the LOFAR can detect signals known as interplanetary scintillation, which provide essential information on the 3D structure of the solar wind near the Sun. This knowledge is important for providing an inner boundary condition to global MHD models and for interpretation of temporal variations in ENA maps. It is also important for constructing ENA maps because solar wind properties across heliolatitudes are necessary to calculate ENA survival probabilities.

Theory, Modeling, and Simulations

Theory, modeling, and numerical simulations are extremely important to the science of the outer heliosphere. Generally, this is supported by small research and analysis grants—including the HTMS program, Heliophysics

Supporting Research Program, and guest investigators—but also by the NASA Drive Science Center "Our Heliospheric Shield" (SHIELD), discussed below. In a recent competition of the Guest Investigator program (Research Opportunities in Space and Earth Science [ROSES] 2019), there were five proposals related to outer heliospheric research. In addition, outer heliospheric research has been supported by the NSF Division of Atmospheric and Geospace Sciences (AGS), which includes the highly successful annual SHINE workshop where there are routinely special sessions that focus on this science.

Global models of the heliosphere provide the basic structure and shape of the heliosphere, as well as the response of its boundaries to variations from the Sun. It is known that these models overestimate the thickness of the heliosheath, and this is a particular focus area of investigation. Is it a time-dependent effect, caused by the solar cycle, or is there missing physics? Global models also reveal intriguing small-scale structures, including those driven Rayleigh-Taylor and other instabilities, as well as features such as a plasma depletion layers and the hydrogen wall—all of which remain to be tested against in situ observations.

Motivation for the Goal

At the beginning of the past decade, researchers still had a fairly rudimentary understanding of the processes that formed and sustained the global heliosphere. At that time, Voyager 1 had just crossed the HP, Voyager 2 was still within the heliosheath, and IBEX had discovered a mysterious Ribbon of enhanced ENA emission that had been entirely unanticipated by the theoretical community. By the end of the decade, both Voyagers had crossed into the LISM, revealing a remarkably steady GCR flux compared to what was observed in the heliosheath, observing the echoes of solar transients in the LISM, and discovering that the magnetic field was still oriented as it had been interior to the HP—implying that it had yet to "unwind" to the expected ISM direction. IBEX observations showed definitively that the heliosheath responds rapidly to changes in solar variability and that the Ribbon was most likely located beyond the HP and was formed by a "secondary ENA" process. New Horizons has shown that by the time the solar wind reaches the outer heliosphere, most of the energy is carried by the PUIs, and thus this population dominates the dynamics of the TS and heliosheath.

Informed by all that has been learned about the heliosphere the past decade, the panel has honed PSG 4 to target the areas where deeper investigation is required to complete the picture of our home in the galaxy. It focuses on exploring what produces spatial and temporal variability, figuring out the shape of the heliosphere, nailing down the origins of the Ribbon, diving into the details of PUI physics across the outer heliosphere and LISM, and solving the mysteries of ACR origination and GCR modulation. The IMAP mission will tackle many of these inquiries, but fully addressing this science goal will require an interstellar probe.

System-Level Science Contributions

The study of how the heliosphere is formed and sustained requires a systemwide understanding of the evolution of the solar wind and the solar magnetic field. The conditions that control the formation of the interstellar boundary are established deep within the inner heliosphere where PUIs are first entrained in the solar wind from an "inner source" of interplanetary dust grains. As the solar wind flows outward, it crosses a huge range of density, temperature, and spatial domains, and thus, achieving a complete picture of the solar wind's physical state from the Sun to HP requires measurements from the whole HSO, including from PSP and SO to ACE, STEREO, IMAP, New Horizons, the Voyagers, and ultimately, an interstellar probe.

PSG 4 is tied to system-level science in another way, as it is closely connected with EO 1, targeting multidisciplinary research focusing on solar and stellar activity. Just as the Sun is Earth's closest star, and thus serves as a laboratory for understanding stars throughout the galaxy, our heliosphere is our closest astrosphere, and its study informs the understanding of other astrospheres and how they interact with their own local ISMs. In turn, through the systematic study of other astrospheres, their diverse properties will be sure to teach us about our heliosphere—not only as it is now, but how it may have been in the past and will be in the future, under different ISM conditions, and thus foretelling the journey of our home as it travels through the galaxy.

B.2.5 Role of Research and Analysis Development Grant Programs

Much of the scientific output of the Sun and heliosphere (SH) community is carried out via smaller grants through programs across agencies. These programs are essential to the health of the SH community because they fund the many researchers not directly supported by space missions or ground facility programs. They also enable research that falls outside the purview of a specific mission's or facility's science objectives.

Current funding opportunities related to SH can be classified in the following five main categories: (1) funding that is closely aligned with mission goals (mission aligned), (2) general funding to advance the understanding of heliospheric physics (general), (3) targeted funding that occasionally focuses on proposals relevant to SH (targeted), (4) funding that focuses on the creation of large overarching collaborations of scientists which aim to enable science that is not possible through small grants (systemic), and (5) programs targeted at instrument technology development and low-cost deployment (instrumentation).

- *Mission-aligned funding opportunities* include NASA's guest investigator programs—both specific (e.g., NASA SO Guest Investigators) and open (NASA Heliophysics Guest Investigator [HGI]).[1]
- *General funding opportunities* include NASA's Heliophysics Supporting Research (HSR) and NSF's Solar Terrestrial and Solar, Heliospheric, and Interplanetary Environment (SHINE), as well as Astronomy and Astrophysics Research Grants (AAG) programs. It is worth noting that while NSF-Astronomy supports construction and operation of large solar facilities (including Inouye and, if successful, the future COSMO and the Frequency-Agile Solar Radiotelescope [FASR]), the AAG is a highly competitive program for general research in astronomy, which implies that no dedicated funding is available for scientific exploitation of such facilities. These funding opportunities are the broadest calls, and they act as an umbrella for many ideas and areas strongly informed by the decadal survey reports. The NASA HTMS program has a strong focus on taking advantage of advances in computational resources to improve the understanding of the heliosphere. Selections in these programs depend on proposal pressure. Moreover, proposal pressure is reasonably related to the occurrence of new missions; for example, there is likely to be an increase in outer-heliosphere proposals when IMAP launches.
- *Targeted funding opportunities* have topics that can change from year to year, often of relevance to SH. The main example of this approach is NASA's Living With a Star (LWS) program, which selects topics based in part on community input.[2] Also of relevance to SH objectives are the Heliophysics Space Weather R2O2R (Research-to-Operations-to-Research) and O2R (Operations-to-Research) programs, which support the development of numerical models and/or data utilization techniques that both advance space weather forecasting capabilities and improved fundamental scientific understanding. Recent thematic opportunities from NSF include the Windows on the Universe—The Era of Multimessenger Astrophysics program, of relevance for many SH topics.
- *Systemic funding opportunities* include NASA's DRIVE Science Centers, which aim to support science that requires more than individual investigators or small teams and were a response to the 2013 decadal survey. Some example centers that this initiative funded are "Consequences Of Fields and Flows in the Interior and Exterior of the Sun" (COFFIES) with the objective to expand the understanding of the Sun to develop the capability to forecast activity cycles and solar magnetic variability, "Our Heliospheric Shield" (SHIELD) with the aim of tackling grand-challenge science questions pertaining to the outer heliosphere, and "Solar Flare Energy Release" (SolFER), whose goal is to understand the release of magnetic field energy and associated particle acceleration in flares in the solar corona. The just-announced opportunity to develop Artificial Intelligence Research Institutes (a collaboration among NSF, the Department of Defense, the National Institute of Standards and Technology, and private foundations or corporations) might prove crucial for research in multiple heliospheric topics.

[1] This paragraph was modified after release of the report to accurately reflect updated process for funding opportunities.

[2] This paragraph was modified after release of the report to accurately reflect the process for selecting topics for targeted funding opportunities.

- *Instrumentation funding opportunities* include the NASA Heliophysics Technology and Instrument Development for Science (H-TIDeS), Heliophysics Flight Opportunities Studies (H-FOS), Heliophysics Flight Opportunities in Research and Technology (H-FORT), and Heliophysics Low Cost Access to Space (H-LCAS) programs. These programs provide a vital pathway for the community to undertake instrumentation development, raise technology readiness, and carry out science demonstration missions, often in anticipation of proposing new instrument concepts for larger NASA missions. Over the past decade, NASA has invested significant resources into these programs, such that there is now a clear progression for researchers to follow from initial concept to flight (e.g., from H-TIDeS to H-FOS to H-FORT). This program is particularly important for those institutions that do not have significant internal program development funding and could otherwise not compete with the major centers.

Within NSF, the Advanced Technologies and Instrumentation for the Astronomical Sciences (ATI) program provides both individual and collaborative research grants for the development of new technologies and instrumentation for use in ground-based astronomy and astrophysics, including innovative technologies and instruments at high technical risk. The Major Research Infrastructure (MRI) program supports the development and acquisition of critical research instrumentation, with the potential to open new opportunities to advance the frontiers in science and engineering research. MRI awards also aim at enhancing research training of students. The Mid-scale Research Infrastructure-1 Program (MSRI-1) supports either the design or implementation of unique and compelling infrastructure projects with costs up to $20 million.

B.3 LONGER-RANGE GOAL

Longer-Range Goal: Revolutionize the understanding of dynamic solar processes through rapid, direct observational measurements of magnetic fields throughout the solar atmosphere and inner heliosphere.

The solar corona and solar wind are largely dominated by magnetic fields, from the low corona into the interplanetary medium (IPM). Such fields are central to how the plasma is heated, how the quiescent solar wind is accelerated, how transients within it are launched, and how energetic particles within it are transported. Progress in understanding these processes is severely curtailed by just how limited capabilities are for measuring field properties beyond the solar photosphere. This LRG is driven by the recognition that new capabilities for measuring coronal and IPM fields must be developed, and then infrastructure built to provide routine coronal and IPM field data products, for both scientific and space weather forecasting purposes. These measurements need to be made on timescales commensurate with dynamic solar activity (e.g., flare energy release timescales that probe localized magnetic field responses beyond globally averaged pre- and post-eruption measurements), are best without reliance on modeling extrapolations, and need to encompass a global view of the activity (versus point measurements or severely limited fields of view). Enabling 3D measurements of the coronal and IPM magnetic fields would constitute the ultimate achievement of this LRG and would revolutionize the understanding of the interconnected fundamental processes throughout the heliosphere.

B.3.1 Motivation and Current Research Activity

Coronal Fields

Most current methodologies for inferring coronal field strengths and orientations rely on extrapolations from photospheric field measurements provided by various ground- and space-based magnetographs. The simplest and still widely used technique is the potential field source surface (PFSS) approach, which dates back to the 1960s and is not computationally expensive. Somewhat more sophisticated are nonlinear force free field (NLFFF) extrapolations. At least for static coronal structures, PFSS and NLFFF extrapolations have been found to be reasonably consistent with more sophisticated MHD modeling, although the quality of agreement with the actual solar corona is less clear.

Field extrapolations from the photosphere naturally carry significant uncertainty, which can be revealed by comparing chromospheric fields predicted by extrapolations from the photosphere with chromospheric magnetograms. Uncertainties can be expected to be even larger higher up in the corona. A new diagnostic technique has recently been developed to measure the magnetic field strength in active regions using a single Fe X line observed by Hinode/EIS. However, this does not provide any direct information on the magnetic field vector orientation and cannot detect the weaker coronal magnetic fields found in coronal holes and the quiet Sun. The limitations of existing indirect techniques for inferring coronal fields are even more pronounced when considering the need to know how coronal fields change during eruptive phenomena, when direct measurement of field strength before, during, and after the eruption are necessary to improve the understanding of the physical processes involved in this activity. Zeeman polarimetry of cooled coronal plasma (observable in typical chromospheric lines such as Ca II or He I in the near-IR) holds promise of alleviating this problem in some cases, offering the opportunity to derive the coronal field strength in post-flare active regions and cold loops, at high spatial and temporal resolution.

An important step toward the remote sensing of coronal fields was the development CoMP, integrated into the Mauna Loa Solar Observatory (MLSO), which observed from 2011 to 2018, diagnosing the magnetic field direction by measuring the linear polarization of coronal Fe XIII lines at 1074.7 and 1079.8 nm. CoMP has since been replaced by UCoMP, which has an expanded field of view and is observing coronal lines at multiple temperatures. An example of how such data can be useful for studying the pre-eruptive states of CMEs is in Figure B-17, which shows a pseudostreamer from April 2015 observed in quiescence with CoMP, but which is later observed erupting in SDO/AIA and SOHO/LASCO. Images of this pseudostreamer from SDO/AIA and MLSO/CoMP are shown in Figure B-17, along with the polarization measurements that lead to inferences about field topology.

A significant limitation of CoMP/UCoMP is its small aperture (20 cm), which makes it infeasible to measure the weak circular polarization component (Stokes V) to derive the field strength or observe with a sufficiently rapid time cadence to study dynamic phenomena. This limitation will be overcome by Inouye. With its 4 m aperture and coronagraphic capabilities, Inouye will provide rapid measurements of the coronal field vector at 1″ resolution, offering unique constraints on both coronal fine structure and field characteristics. However, the field of view of Inouye is limited to only ~5′. Thus, capturing eruptive phenomena will almost certainly require a global field of view, such as for the proposed 1.5 m COSMO telescope. Ground-based observatories always have limitations of nighttime and inclement weather. Observing from space would alleviate such issues and also would provide spectropolarimetric opportunities outside the IR. The potential of H Lyman-α coronal spectropolarimetry in the UV is being explored, with instrument concepts such as Coronal Lyman-Alpha Resonance Observatory (CLARO) and mission concepts proposed in community input papers, such as COMPLETE ("A Flagship Mission for Complete Understanding of 3D Coronal Magnetic Energy Release").

A disadvantage of optical/IR approaches to measuring coronal fields is that they can only do so above the limb and not on the disk. This constraint does not apply in the radio, where the Stokes V signal of the coronal magnetic field via thermal free–free emission is prominent in both locations. Despite the potential of radio observations for deriving the detailed morphology of coronal cavities (both on the limb and against the disk) and accurately mapping line-of-sight field strength, current radio facilities do not have the adequate imaging fidelity, dynamic range, and polarization purity necessary to make such measurements. EOVSA represents a pathfinder for future arrays that could make such measurements. A strong flare from September 2017 provided an opportunity for EOVSA to show radio's potential for dynamic field measurements. Figure B-3 shows how during this event EOVSA measured both the dynamically changing magnetic field strength and connectivity of the erupting source as well as the spatially and temporally evolving electron distribution function, placing new constraints on the magnetic energy release in the flaring source.

Inferring coronal field properties from spectropolarimetric data, whether optical/IR or radio, requires a significant effort to model such data. Various codes have been published to do such analyses and could be further developed (e.g., FORWARD, Coronal Line Emission Database [CLEDB], and Python package for Coronal Emission Line Polarization [pyCELP]), with the goal of using all available information (e.g., multiple lines) to infer the full vector magnetic fields under distinct sets of assumptions. Tomographic techniques are also an active area of research. Currently, all polarimetric methodologies are subject to degeneracies, and suitable disambiguation methods have not yet been developed. Devising an inversion method that leverages both polarization and velocity information appears promising, and a goal to be implemented in the near future.

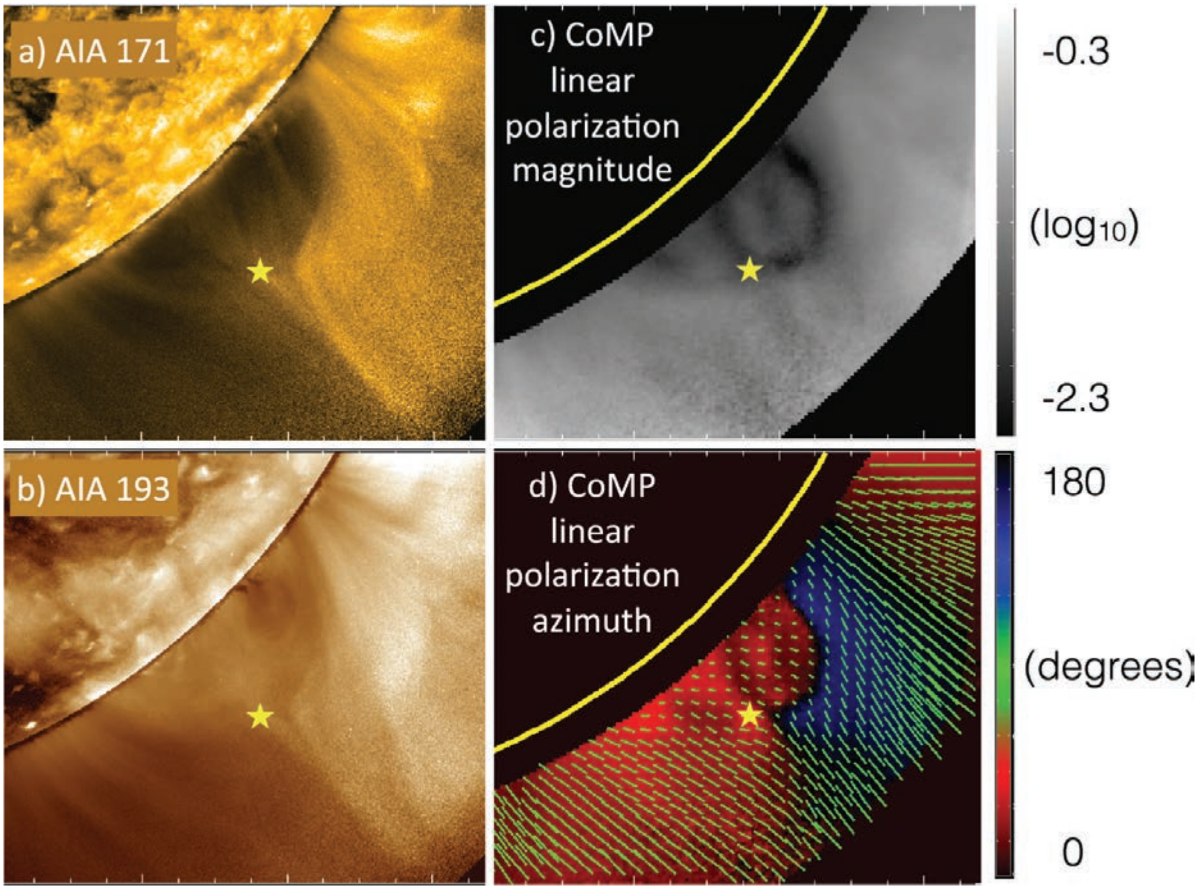

FIGURE B-17 Observations of a pseudostreamer from Solar Dynamics Observatory/Atmospheric Imaging Assembly (AIA) (panels a and b) and Mauna Loa Solar Observatory/Coronal Multi-Channel Polarimeter (CoMP) (panels c and d), the latter of which show polarization measurements that can lead to inferences about magnetic field geometry. Yellow stars mark the intersection of the two lobes of the pseudostreamer.
SOURCE: S. Gibson, K. Dalmasse, L.A. Rachmeler, et al., 2017, "Magnetic Nulls and Super-Radial Expansion in the Solar Corona," *Astrophysical Journal Letters* 840:L13, https://doi.org/10.3847/2041-8213/aa6fac. © AAS. Reproduced with permission.

Interplanetary Fields

Analogous to the situation for coronal fields, the only current way to model interplanetary fields in a global sense is to extrapolate upward from photospheric fields provided by magnetograms. A PFSS model is generally used to provide field magnitudes at the source surface (typically at 2.5 $R_{\odot}$), where the field is assumed to become purely radial. A time-dependent, data-driven MHD code is then used to extrapolate into the IPM all the way to 1 AU, and beyond if required. The PFSS model not only provides field boundary conditions at the source surface but also generally provides solar wind velocity information as well, using the semi-empirical WSA technique relating field expansion factors to solar wind speed. The MHD code used by the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) for this purpose is called Enlil, which not only provides predictions for quiescent wind at Earth, but also provides a model of the ambient solar wind into which CMEs can be launched. With constraints on a CME's initial velocity, spatial extent, and trajectory direction provided by space-based coronagraphs, Enlil therefore offers a real-time forecasting capability for predicting CME arrival time at Earth.

Such modeling naturally has significant limitations. Although it has some demonstrated success at roughly reproducing wind properties observed at 1 AU; it is not, for example, helpful for predicting the north-south magnetic field component (Bz) during CME impacts at Earth, which is the quantity that is most predictive of geoeffectiveness. Predicting Bz or studying interplanetary plasma physics processes in any detail requires the kind of detailed information about IPM field properties that can only be provided by direct measurement. Observationally, almost everything that is known about IPM fields comes from spacecraft equipped with magnetometers. Such spacecraft currently include dedicated solar wind sentinels at 1 AU, such as Wind, ACE, and DSCOVR operating at the Sun-Earth Lagrange 1 (L1) point; and STEREO-A, which drifts in longitude relative to Earth by about 22 degrees of heliographic longitude per year per year. The magnetometer-equipped IMAP and the Space Weather Follow On L1 mission (SWFO-L1) spacecraft will soon join the L1 contingent of spacecraft when launched in 2025. The PSP and SO missions are currently studying IPM fields inside 1 AU. There are also various planetary missions that include magnetometers, such as BepiColombo operating inside 1 AU, and Mars Atmosphere and Volatile EvolutioN (MAVEN) outside 1 AU at Mars. Notably, New Horizons does not have a magnetometer, thus handicapping the ability to track evolution of the IPM into the outer heliosphere.

Spacecraft are point probes of local IPM plasma properties, and therefore only provide 1D tracks through solar wind structures, which is a problem when trying to study IPM physical processes or infer large-scale morphology. For example, the dominant paradigm for CME structure is the magnetic flux rope (MFR). A schematic representation of an MFR is in the left panel of Figure B-18, and if it is viewed edge-on, it would look something like the PSP/WISPR image in the right panel. A number of methodologies exist for inferring 3D MFR structures from 1D plasma and field tracks provided by individual spacecraft. However, these extrapolations from 1D to 3D rely on many dubious assumptions, and there are often large discrepancies between MFR structures inferred from in situ data and those inferred from imaging. Significant improvement could be realized if a CME could be sampled by many spacecraft, collectively providing a more comprehensive 3D picture of the CME's structure and providing more stringent tests of the MFR paradigm. This need is one argument for the development of constellation mission concepts, involving the coordination of multiple spacecraft to study IPM structures and processes. It has already become increasingly common for CME analyses to utilize multiple spacecraft, but currently this relies on chance alignments of existing missions within the HSO architecture.

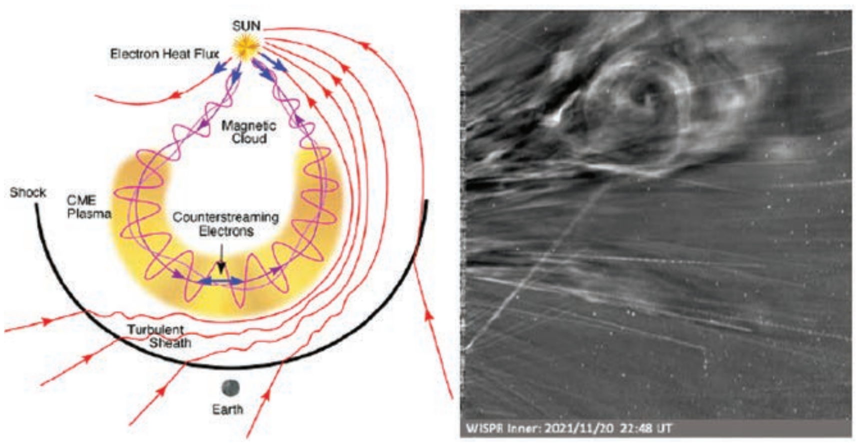

FIGURE B-18 Schematic picture of the magnetic flux rope (MFR) paradigm for coronal mass ejection (CME) structure (*Left*), compared with a CME image from Parker Solar Probe/Wide-Field Imager for Parker Solar Probe (WISPR) (*Right*) showing and edge-on view of a magnetic flux rope of similar geometry passing across the instrument field of view. It is extremely difficult to reconstruct MFR structure from the one-dimensional track of a spacecraft through the event.
SOURCES: (*Left*) T.H. Zurbuchen and I.G. Richardson, 2006, "In-Situ Solar Wind and Magnetic Field Signatures of Interplanetary Coronal Mass Ejections," *Space Science Review* 123:31–43, reproduced with permission from SNCSC; (*Right*) Howard et al. (2022), https://doi.org/10.3847/1538-4357/ac7ff5. CC BY 4.0.

Constellations with smaller spacecraft separations are needed to study smaller-scale IPM processes, such as turbulence, particle acceleration, and magnetic reconnection. Such constellations currently include the magnetosphere-focused MMS mission, and the future HelioSwarm mission to explore the near-Earth solar wind, with a possible launch date in 2028. A focus of HelioSwarm will be to determine the dynamical nature of solar wind turbulence. While missions like MMS and HelioSwarm focus on kinetic or microscales, and NASA's HSO concept focuses on macroscale IPM structures, it has been noted that there is an intermediate-size scale that is relatively unexplored, which has been given the term "mesoscale." Kinetic scales represent the end of the turbulent cascade that is driven by large-scale solar wind structures. The intermediate mesoscale dynamics represents the critical scale needed to understand cross-scale processes in the solar wind. Last, the experience of missions like MMS demonstrates that interpreting plasma and field data from constellations requires not only the multispacecraft sampling itself, but also support for the research necessary to interpret the data, including theory, simulation, and laboratory experiments.

The ideal observational diagnostic for IPM fields would be one involving remote sensing, allowing solar wind and CME fields to be probed from a distance. Currently, the only remote sensing candidate is radio Faraday rotation, which provides a diagnostic of both the strength and orientation of the magnetic field along the observed line of sight to any background polarized radio source. The Faraday rotation signatures of CMEs have been probed with interplanetary spacecraft as background sources. Astrophysical background sources (e.g., pulsars or active galactic nuclei) can also be used, but their faintness means that a powerful radio array such as VLA or LOFAR must then be utilized to observe the signal. The community input paper concept for the MOST mission proposes the deployment of four 1 AU spacecraft spaced along a semicircular span of helio-longitude, each equipped with a radio receiver/transmitter to make Faraday rotation measurements between the spacecraft along four lines-of-sight crossing the inner heliosphere. Figure B-19 shows an example of using VLA to probe CME field structure.

B.3.2 Why Is This a Longer-Range Goal?

In contrast to 30 years ago, we are now living in an era where high-resolution, high-quality photospheric magnetograms are continuously available, and it is assumed that this will continue in perpetuity. Likewise, space-based missions now provide synoptic EUV and/or X-ray observations of the low and middle corona, and white-light coronagraphs continuously monitor the upper corona and catalog CMEs erupting into the IPM. Once again,

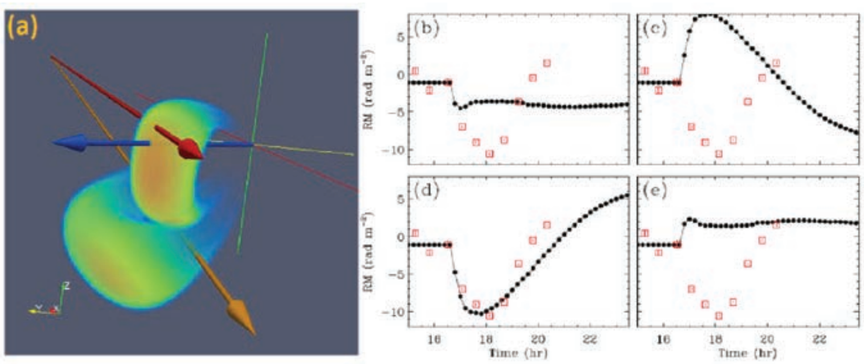

FIGURE B-19 (a) Reconstructed flux rope structures of two coronal mass ejections (CMEs) from August 2, 2012. The blue arrow indicates the Solar Terrestrial Relations Observatory (STEREO)-A's direction, and the red and orange arrows indicate the lines of sight from Earth toward two background radio sources observed by the Very Large Array (VLA). (b–e) The red data points show the VLA rotation measures for the orange arrow line of sight, compared with predictions based on four different assumed field polarities for the field inside the flux rope shape shown in (a). The polarity assumed in (d) clearly provides the best match to the data, demonstrating how radio Faraday rotation observations can be used to infer CME field structure.
SOURCE: B.E. Wood, S. Tun-Beltran, J.E. Kooi, E.J. Polisensky, and T. Nieves-Chinchilla, 2020, "Inferences About the Magnetic Field Structure of a CME with Both In Situ and Faraday Rotation Constraints," *Astrophysical Journal* 896:99, https://doi.org/10.3847/1538-4357/ab93b8. © AAS. Reproduced with permission.

it is commonly assumed that this coronal monitoring will continue in perpetuity, in some form, for both scientific research and for space weather–forecasting purposes. However, none of this coronal monitoring provides direct magnetic field information and is heavily reliant on modeling. A long-term plan for developing the ability to supplement synoptic magnetograms with 3D coronal field maps in the low and middle corona could yield transformational advancements in coronal physics. Likewise, developing the ability to monitor fields in the IPM would markedly advance studies of interplanetary plasma physics and provide new space weather forecasting capabilities, particularly Bz forecasting at Earth for geoeffective transients. None of this is attainable in the timescale of a single decadal survey period, because the ideal techniques for measuring coronal and IPM fields are not yet established. Thus, the development of a coronal/IPM field monitoring infrastructure must be considered a longer-range goal.

B.4 EMERGING OPPORTUNITIES

B.4.1 Emerging Opportunity 1

Emerging Opportunity 1 (EO 1): Enable opportunities for multidisciplinary research to holistically explore how solar and stellar activity and the interactions of stars with their interstellar environments impact planetary systems.

Recent years have seen an exploding interest in establishing how stellar winds, flares, CMEs, and the local interstellar environment affect exoplanets and their habitability. EO 1 seeks to support these interests and to take advantage of frontier research and astrophysical/solar instrumental resources by encouraging interdisciplinary heliophysics/astrophysics studies of solar and stellar activity and of astrosphere/interstellar medium interactions. Understanding stellar activity relies heavily on solar observations, because the Sun is the only star that can be observed in proximity. However, solar physics can also benefit from stellar observations. For example, observations of Sun-like stars of different ages and activity levels inform about what solar activity might have been like in the past, and what it might be like in the future.

Motivation and Current Activity

Solar/Stellar Flares

Many stars are known to produce flares analogous to solar flares, albeit some with energies that are 1,000–10,000 times larger than are experienced from the Sun. The observational literature on solar and stellar flares is vast, with both solar and stellar flares being observed at wavelengths ranging from radio to gamma rays, and everything in between. However, the lack of spatial resolution for stars means that relatively little is still known about how stellar eruptive processes differ fundamentally from the Sun. Thus, the solar example provides guidance for modeling efforts that seek to understand stellar data. The most active stars rotate much faster than the current-day Sun, and they in turn provide a glimpse into the high-energy radiation environment of the early solar system.

Besides spatial resolution, another advantage of solar flare studies is continuous monitoring. A number of ground- and space-based solar observatories, past and present, have provided continuous monitoring of the Sun at various wavelengths, allowing a large number of solar flares to be studied comprehensively. Multiwavelength coverage of stellar flares is rarer, given the logistical arrangements for a flare-monitoring campaign with a variety of highly competitive ground- and space-based assets. Radio gyrosynchrotron observations at optically thick (2–10 GHz) and thin (>10 GHz) frequencies are available for both solar and stellar flares, and they offer comparative opportunities to study the properties of particle acceleration within different stellar magnetic environments. However, there are almost no optical observations of solar flares that are analogous to those that are widely available for stellar flares (e.g., from Kepler, the Transiting Exoplanet Survey Satellite [TESS], and broadband spectroscopy). Instead, solar observations emphasize high spatial and spectral resolution to the detriment of large spectral coverage. Figure B-20 represents a comparison of how solar and stellar flares are observed in the optical/near-UV, with a spatially resolved image of a solar flare site, with only single-line spectroscopy available in

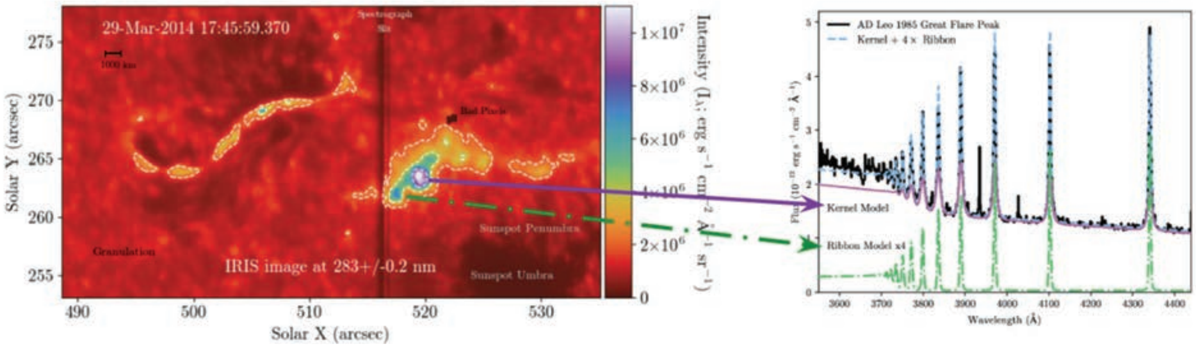

FIGURE B-20 On the left, a spatially resolved solar flare image from Interface Region Imaging Spectrograph (IRIS), showing flare ribbons including the strongest emission kernels (green and purple). On the right, a stellar "superflare" spectrum from the active M dwarf star AD Leo, showing strong emission from the hydrogen Balmer lines and the optical continuum. Colored lines are model predictions.
SOURCE: Kowalski (2022), https://doi.org/10.3389/fspas.2022.1034458. CC BY 4.0.

selected points, shown next to a stellar superflare spectrum covering all the H Balmer lines observed from an M dwarf star. These stars are thought to be the most common hosts of habitable zone exoplanets.

A holistic understanding of the physical origin and environmental effects of stellar eruptive events relies on leveraging advances in imaging spectroscopy and radiative MHD modeling of the Sun over the next decade. Even with the unprecedented successes of IRIS in observing solar flare dynamics over the past decade, much is still poorly understood about the critical impulsive phase at the onset of solar flares, and by extension, stellar flares. Better comparison of solar and stellar flare characteristics could be enabled by new solar capabilities to capture spectra over a 2D region simultaneously with sufficient spatial, spectral, and temporal resolution across a wide wavelength range containing most of the optical diagnostics that are commonly observed in stellar flares. The future Multi-slit Solar Explorer (MUSE) mission represents an important step toward simultaneous spectroscopy and 2D imaging, albeit in the EUV. New solar imaging spectroscopic capabilities utilizing developments in integral field technologies will forge novel pathways that leverage the vast archives of stellar data from ground-based observatories and NASA's space missions (e.g., Kepler, TESS). This technology will naturally complement the recent directions in the advancements in radio imaging spectroscopy (e.g., with EOVSA; Figure B-3) of the magnetic field changes and particle acceleration that power solar eruptive events.

The emerging capabilities of new solar MHD codes and techniques will be leveraged and extended to the astrophysical environments of stars, providing the needed physical information on spatial scales extending from the chromosphere to the wider realm of the astrosphere and ISM, which modulate GCRs and habitable zone conditions.

Solar/Stellar Winds, Coronal Mass Ejections, and Astrospheres

Coronal winds analogous to that of the Sun are unfortunately very hard to observe around other stars. The most successful technique for studying stellar winds so far is by using UV spectra from the Hubble Space Telescope to detect H Lyman-α absorption from interaction regions between the winds and the surrounding interstellar medium—that is, astrospheric absorption. With guidance from MHD models, mass loss rate estimates can be inferred from the astrospheric absorption, and an example of such an astrospheric model is shown in Figure B-21(b). These model astrospheres are computed using codes first developed to model the global heliosphere, such as that in Figure B-21(a). The astrospheric absorption diagnostic has so far provided only 22 mass loss rate measurements (plus a number of upper limits). Furthermore, this diagnostic is measuring the average wind ram pressure over long timescales, typically years to decades depending on the size of the astrosphere. Thus, it is unknown whether the detected stellar winds are dominated by quiescent wind or CMEs.

Stellar CME candidates are typically found via observations that are not the means by which solar CMEs are studied, meaning that it is not entirely certain that the same phenomenon is being seen. A number of stellar CME

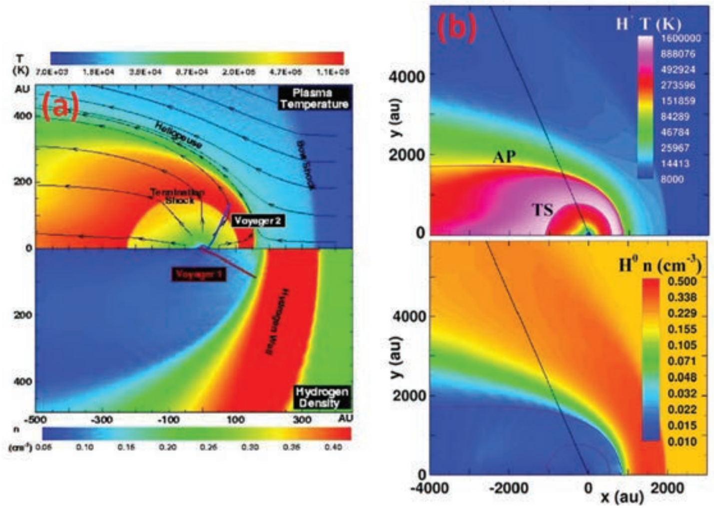

FIGURE B-21 Magnetohydrodynamic models developed to model the global heliosphere can be applied to astrospheric modeling. Shown in (a) are proton temperature (top) and neutral hydrogen density (bottom) for a 2.5D) axisymmetric model of the heliosphere, showing how the radial solar wind emanating from the origin interacts with the interstellar wind flowing from the right. Shown in (b) is an analogous astrospheric model for the active M dwarf flare star YZ CMi, with the straight black line indicating the line of sight to the star, along which detectable Lyman-α absorption was observed by the Hubble Space Telescope. The absorption observations are used to infer the stellar wind mass loss rate, which when modeled, leads to a particularly large astrosphere. The astropause (AP) and termination shock (TS) boundaries are indicated in the top panel. SOURCES: (*Left*) Müller and Zank (2004); (*Right*) B.E. Wood, H. Muller, S. Redfield, et al., 2021, "New Observational Constraints on the Winds of M Dwarf Stars," *Astrophysical Journal* 915:37, https://doi.org/10.3847/1538-4357/abfda5. © AAS. Reproduced with permission.

claims originate from detection of blueshifted H-α emission or absorption after stellar flares. On the Sun, such observations would be called signatures of prominence/filament eruptions, or chromospheric evaporation into confined structures. While there are certainly cases where prominence material ends up incorporated into a CME that escapes the Sun, this is not always the case, so an H-α signature by itself would not necessarily be considered an unambiguous CME detection. Blueshifted coronal lines observed in SXR spectra after stellar flares have also been observed and interpreted as a CME signature.

One solar CME detection technique that does have potential applicability to how stars are observed is coronal dimming, demonstrated using full-disk SDO Extreme ultraviolet Variability Experiment (EVE) observations of low-temperature coronal lines like Fe IX at 171 Å. In stellar SXR observations, there are post-flare coronal dimmings that have been observed, which have been interpreted as possible CMEs. Figure B-22 compares a coronal dimming seen in a Sun-as-a-star spectrum from SDO/EVE with a post-flare dimming seen for the M dwarf Proxima Cen in XMM-Newton SXR data. However, in broadband SXR observations of the Sun there can be dimmings that are intrinsic to the active region and not associated with a CME.

Type II radio bursts are another promising stellar CME detection technique that relates well to how CMEs are observed on the Sun. Such observations would have the added benefit of indicating the CME speed through the rate of change in radio frequency. Unfortunately, attempts to detect type II bursts from frequently flaring M dwarfs have so far proved unsuccessful. The stellar type II nondetections call into question the existence of fast, massive CMEs that are generally assumed to accompany the extremely energetic flares from M dwarf stars. Further evidence for this comes from the modest mass loss rate measurements for active M stars from the astrospheric absorption technique, suggesting that the frequent and energetic flaring is not always accompanied by massive CME eruptions.

The Sun itself may provide clues for what is happening on active flare stars, as there are many cases of strong flares with no associated CME. A well-studied example from October 2014 is a series of X-class flares from active

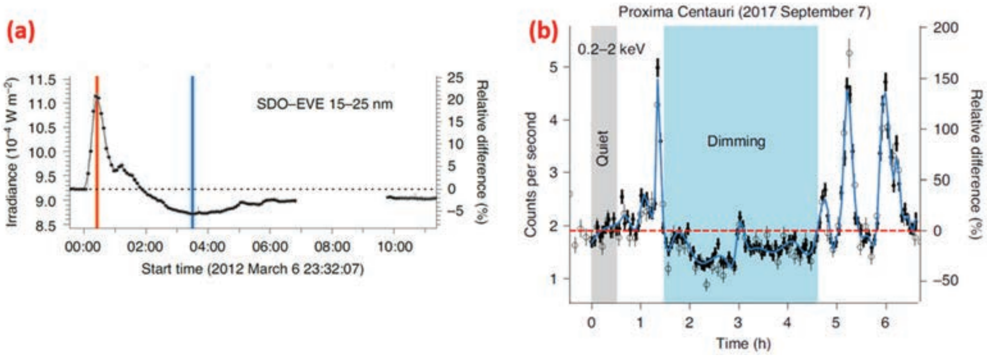

FIGURE B-22 (a) A disk-integrated extreme ultraviolet (EUV) light curve for the Sun in March 2012, showing a solar flare (red line) followed by a coronal dimming (blue line) associated with a coronal mass ejection (CME). (b) XMM-Newton (High Throughput X-ray Spectroscopy Mission and the X-ray Multi-Mirror Mission) X-ray light curve for the active M dwarf Proxima Cen from September 7, 2017, showing a stellar flare followed by a dimming event that could be indicative of a stellar CME.
SOURCE: A.M. Veronig, P. Odert, M. Leitzinger, K. Dissauer, N.C. Fleck, and H.S. Hudson, 2021, "Indications of Stellar Coronal Mass Ejections Through Coronal Dimmings," *Nature Astronomy* 5:697–706, reproduced with permission from SNCSC.

region (AR) NOAA 12192, the largest AR of solar cycle 24. Almost none of the flares from AR 12192 had associated CMEs. On the Sun, this is unusual, but on active stars perhaps it is the norm. Strong magnetic fields overlying an active region can inhibit CME eruption. Numerical simulations of CMEs on active stars made in recent years include models of such confined eruptions.

Aside from their role in providing a rare means by which stellar winds can be detected, astrospheres are also of interest because they provide protective cocoons for life on potentially habitable planets, shielding them from harmful GCRs. On long timescales, the nature of astrospheric structures can change dramatically as different interstellar environments are encountered. Extreme examples include very dense molecular clouds and supernova shock waves, both of which can potentially compress the heliosphere and astrospheres enough to place planets outside their protective boundaries. There is evidence that events of this sort occurred as recently as 2–3 million years ago to the heliosphere, with possibly drastic effects on Earth's climate and biological systems. Models of the global heliosphere and astrospheres are being used to assess the impacts of such encounters.

Modeling Stellar Winds

MHD modeling of stellar winds/CMEs and their interactions with exoplanets began not long after exoplanets were discovered. Some stellar wind models are very reminiscent of Enlil-like solar models, using photospheric magnetograms, a PFSS extrapolation, and the WSA prescription to provide field and velocity estimates at the inner source surface boundary. This estimation is enabled by ground-based stellar spectropolarimetric monitoring that has recently provided crude stellar magnetograms even for relatively inactive, slowly rotating stars, information that had not long ago been available only for the most active and rapidly rotating of stars. However, the spatial resolution of such stellar magnetograms is naturally much lower than for the Sun.

Other types of stellar modeling include a coronal model at an inner boundary condition, constrained by coronal emissions, using empirical knowledge of how solar emission and magnetic fields are related. Such stellar modeling often relies on flux–flux scaling relations, such as those relating X-ray flux to H Lyman-α flux. Comparisons are made between the relations derived from the Sun and those that are possible from stars. Fluxes from optically thick lines are sometimes used as magnetic proxies on other stars.

It appears that the most detrimental effects on exoplanet atmospheres would be caused by a scaled-up Carrington CME and its associated energetic protons, rather than the electromagnetic effects of a large flare, but as noted above, our knowledge of the characteristics of stellar CMEs is very limited. Many MHD models that seek to study this numerically utilize the same codes used to model solar wind/CME propagation in the heliosphere, and interaction with Earth's magnetosphere. Enhanced eruption energies or accelerated particle fluxes are assumed to explore magnetic eruptions and atmospheric heating in particularly active stars, with potential ramifications for the habitability of exoplanets around such stars.

The current modeling approach attempts to embed the simulations in a realistic stellar environment—in terms of magnetic topology, magnetic field strength, and gravitational acceleration—all of which may be significantly different from the Sun. The various plasma instabilities, from those that trigger eruptions to those in the process of high-energy particle propagation, take on different thresholds and behaviors in the conditions that are inferred in stellar environments. For example, for active stars there is the likelihood of stronger overlying fields and larger coronal densities compared to the Sun, which could in principle inhibit CME eruption. As empirical extrapolations require both radiative and particle fluxes for assessments of the exoplanet environments, a holistic approach that incorporates both in models is required. This integration also includes particle acceleration models, which in a solar context have achieved important advances in reproducing power-law distributions over many decades in energy through magnetic island circularization and coalescence. These particle acceleration models have not yet been applied to other stellar environments.

Exoplanet transit observations are most known for allowing the detection of exoplanets around other stars, and in some cases for studying extended exoplanetary atmospheres by detecting atmospheric absorption during transit. However, the photometric transit profiles can also be used to resolve stellar surface features that are otherwise unresolvable. Stellar surface brightness variations can be inferred from the transit light curves, which can test models of stellar surface flux based on extrapolations from the Sun. Further advancement can only be achieved through better knowledge of magnetoconvection using the sophisticated treatments of MURaM, Bifrost, Stagger, COnservative COde for the COmputation of COmpressible COnvection in a BOx of L Dimensions with l=2,3 (CO5BOLD), and so on, with the ultimate goal of modeling the 3D time-dependent stellar atmospheric structure from the photosphere through the corona. These models can be advanced to not only help provide better heterogeneous models of stars based on current advances in heliophysics, but they would also shed light into the otherwise unknown missing processes in the solar paradigm, which derives from a single star over one small fraction of time within its entire life. Further advancements in MHD models that have been developed for the study of spatially resolved radiative phenomena observed on the Sun can provide answers about the origin of physical processes behind the flux–flux scaling relations of stars and other stellar phenomena, many of which are now thought to be relevant to prebiotic chemistry in exoplanet atmospheres and the development of planetary systems. An important example is the origin of flare quasi-periodic pulsations, which have been observed in many types of stars and in the Sun.

Why Is This an Emerging Opportunity?

The topic of stellar activity and its effects on exoplanets is one that seems more central to stellar astrophysics and planetary science than heliophysics, but given that knowledge of the nearby Sun will always greatly exceed that of any other star, solar physics has a crucial role to play in this research. The discovery of the first exoplanet orbiting a Sun-like star in 1995 is undoubtedly one of the most important astrophysical developments in recent history, even winning a Nobel Prize in Physics in 2019. The number of known exoplanets has ballooned to more than 5,000. Most known exoplanets orbit very close to their stars, magnifying the potential impact of stellar activity on these planets. These include habitable-zone exoplanets around faint M dwarfs (see Figure B-23), which are particularly numerous and can be surprisingly active. Understanding stellar activity will therefore remain a very important astrophysics goal for some time. However, studying activity on distant stars is much harder than studying solar activity, so stellar understanding will necessarily rely heavily on the solar example, and this research must therefore engage the heliophysics community as well.

There is also a need for creating mechanisms for collaborative synergies in basic and applied studies of solar and stellar eruptive events. Improving support for such cross-disciplinary research includes encouraging heliophysics research that is motivated in part by considerations of the wider astrophysical community. For example, many of the same numerical modeling codes that have been developed to model the solar wind and its magnetospheric interactions have also been used to model stellar winds and exoplanet interactions. As a result, considering the

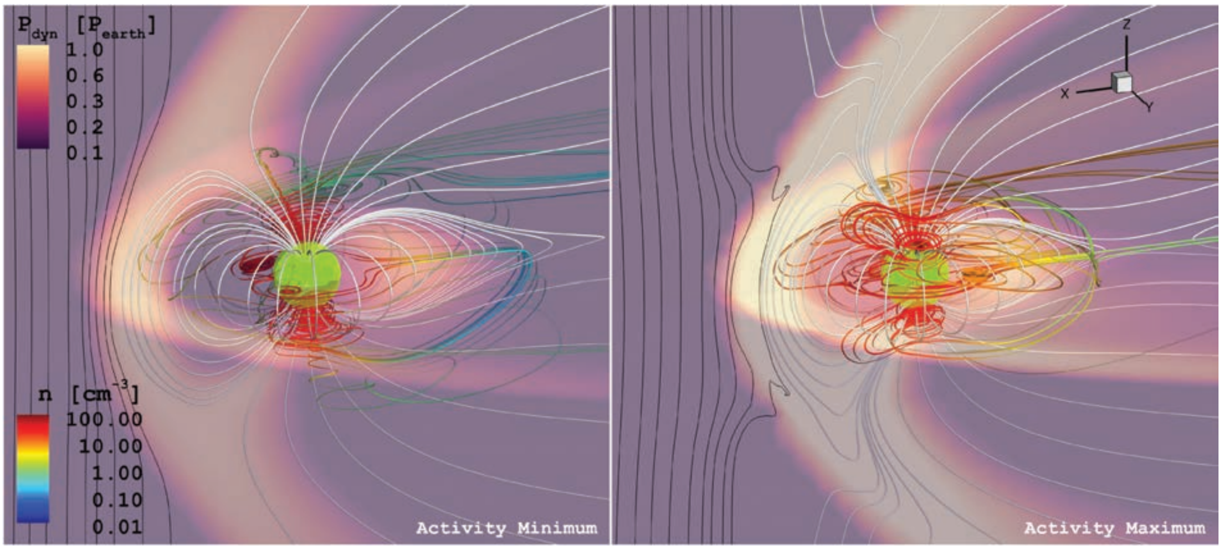

FIGURE B-23 Magnetohydrodynamic model of the interaction of the stellar wind of the active M dwarf Proxima Cen interacting with the orbiting exoplanet, Proxima c, at a minimum (*Left*) and maximum (*Right*) state of stellar activity. It is worth noting that models of this sort are often based on codes developed by heliophysicists for modeling the solar wind and its magnetospheric interactions.
SOURCE: Alvarado-Gomez et al. (2020), https://doi.org/10.3847/2041-8213/abb885. CC BY 4.0.

needs of both solar and stellar communities would support further development of such codes. Another example concerns stellar CMEs. As noted above, there is increasing evidence that the frequent, very energetic flares seen from very active stars may not be accompanied by massive CMEs, suggesting that such flares may be confined eruptions, as are sometimes observed on the Sun. This provides increased motivation for future studies of these confined solar eruptions, in order to better understand the coronal environments that lead to them, which may be more common on active stars than they are on the Sun.

It would also be beneficial for funding agencies to explicitly provide more opportunities for cross-disciplinary studies between the heliophysics, astrophysics, and planetary communities. This could involve, for example, coordinated "centers of excellence" support, analogous to the NASA Astrobiology Institutes, the Heliophysics DRIVE centers, or the joint NSF/NASA funding structures that have supported multiple-institution space weather research networks. Narrower efforts could be supported through existing funding programs within NASA and NSF. For example, within NASA, the Heliophysics Division could offer support through targeted cross-disciplinary focus science topics chosen for funding within the LWS program. Within the Astrophysics and Planetary Science divisions, support could be offered through an expanded Exoplanets Research Program or Habitable Worlds Program, designed to encourage participation of the heliophysics community.

B.4.2 Emerging Opportunity 2

Emerging Opportunity 2: Leverage upcoming opportunities through the lunar, Mars, and planetary exploration programs to enable cross-cutting solar and heliospheric research from emerging platforms and unique environments.

Human activities on and near the Moon, planned to begin in this decade, are significantly impacted by processes originating at the Sun, such as high-energy particle radiation associated with SEPs, and possibly deleterious effects stemming from the solar wind interaction with the Moon and planetary atmospheres. Heliophysics provides critical support for, and also stands to benefit from, the lunar, Mars, and planetary exploration programs that are core to NASA's mission priorities. EO 2 leverages these programs to enable unique and practical SH research while benefiting deep space expeditions. Several heliophysics mission and instrumentation concepts provide critical observations and measurements that support such exploratory endeavors. Conversely, these deep space exploration programs provide unique opportunities for heliophysics to study multiscale processes occurring in the lunar and Martian environment, which is important, and connected to, the general understanding of the heliospheric environment.

Motivation and Current Activity

Emerging Exploration Programs and Infrastructure

The Artemis program is a major endeavor being undertaken by NASA with commercial and international partners to establish and maintain a human presence on the Moon and in cislunar space. The technologies developed and lessons learned from these deep space habitation efforts will propel the next major leap toward human exploration of Mars. The infrastructure being developed and built for these efforts will provide exciting and unique opportunities that can enable heliophysics and space weather research with additional emphasis needed on space weather forecasting and nowcasting.

- *Lunar surface:* The primary objective of the Artemis program is to establish exploratory base camps on the lunar surface, transporting astronauts from orbit to the surface via the Human Landing System. These locations could serve as opportunities for heliophysics research on the lunar surface through measurements enabled by access to unique environments with the aid of human intervention that would be otherwise unobtainable.

  The Commercial Lunar Payload Services (CLPS) is a collaboration between NASA and industry that facilitates delivery of a variety of commercial services and payloads to the Moon. Heliophysics science can provide considerable support to these commercial endeavors. Indeed, one of the first payloads selected to be delivered by CLPS (Lunar Environment Heliospheric X-ray Imager [LEXI]) will study the interaction between Earth's magnetosphere and the solar wind.
- *Cislunar space: Gateway* is a lunar orbiting space station that will serve as an outpost for astronauts in the Artemis program and can serve as an excellent opportunity for heliophysics science in cislunar space (i.e., within the Moon's orbit). The station can host instruments, both external and internal, to study the Sun and the deep space environment. *Gateway* will have a uniquely situated orbit about the Moon's poles that enables measurements both within Earth's magnetosphere and within the unprotected space radiation environment, providing solar viewing opportunities as well as exposure to GCRs and intense SEP events. The platform is an ideal outpost for measuring these particles in a planetary environment. To that end, the initial manifest for *Gateway* includes pathfinder external instrument suites provided by NASA (Heliophysics Environmental and Radiation Measurement Experiment Suite [HERMES]) and ESA (European Radiation Sensors Array [ERSA]) to measure high-energy-particle radiation with the expectation of future payload opportunities.

  Additional infrastructure capabilities associated with *Gateway* are currently in the concept, design, and/or development phase. For instance, logistics modules will be used to transport cargo and supplies to *Gateway* and have the potential to serve as additional observational platforms for instrumentation post-delivery. CubeSat deployment from *Gateway* into cislunar space is another potential science-enabling capability (e.g., using the moon as a coronagraph to study the solar corona) to consider for advocacy by the Heliophysics Division.
- *Communications:* Currently, spacecraft in the HSO rely heavily on an oversubscribed Deep Space Network. The LunaNet (or lunar internet), which is aimed at supporting lunar exploration, activities, and eventually beyond, is an important opportunity to provide an additional resource for an expanding network of spacecraft and payloads.

As these infrastructure opportunities begin to take shape, the science community stands to benefit greatly from increased engagement between the Heliophysics Division and the CLPS, Gateway, and LunaNet programs to identify synergies, to provide capability requirement inputs, and to expand and highlight payload opportunities.

Heliophysics and the Moon

In 2007, the Subpanel for Heliophysics Science and the Moon to the NASA Advisory Council Heliophysics Subcommittee published the report *Heliophysics Science and the Moon: Potential Solar and Space Physics Science for Lunar Exploration*, which identified numerous ways that the science of heliophysics will benefit from the now imminent exploration of the Moon as part of the Artemis program. Figure B-24 from this report illustrates a few of the many important plasma physics–related processes that result from the Sun's interaction with the Moon.

The interaction of the Moon with the solar wind, Earth's magnetosphere, and energetic particle radiation environment represents an ideal environment for studying a range of solar and heliospheric science problems over a broad range of scales. Below, the panel lists several specific heliophysics science problems that would significantly benefit from increased exploration of the lunar environment.

- *Lunar magnetic fields and solar wind interaction:* The Moon does not have a global magnetic field like Earth; however, there are numerous localized concentrations of magnetic fields (magcons) that dot its surface. They are often found in close correlation with craters and also seem to correlate with albedo features on the Moon, known as lunar swirls. These magcons are strong enough to provide small-scale mini-magnetospheres that shield the lunar surface from the solar wind.

  The interaction of the solar wind with a magcon is a kinetic physics process that is likely complicated by interactions with high-albedo lunar swirls. The albedo of the Moon depends on the impact history of the solar wind via space weathering, and the swirls are thought to be regions that are shielded from the impact of the solar wind. Close study of this, especially on the lunar surface, would establish, or rule out, this explanation. The interaction with the magcons is also known to be associated with the reflection of solar wind ions, even before they strike the lunar surface (Figure B-25), which has been detected by previous lunar-orbiting spacecraft. These ion beams can lead to further plasma instabilities at altitudes a few hundred kilometers or more above the lunar surface. Targeted observations are needed to understand the creation and consequences of these instabilities.

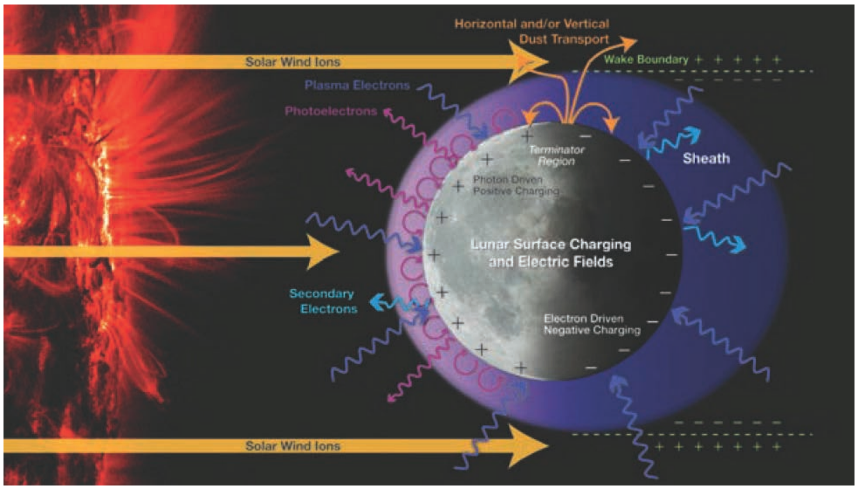

FIGURE B-24 Diverse nature of the interaction of the solar wind with the Moon, creating a unique environment rich in plasma physics.
SOURCE: NASA (2007).

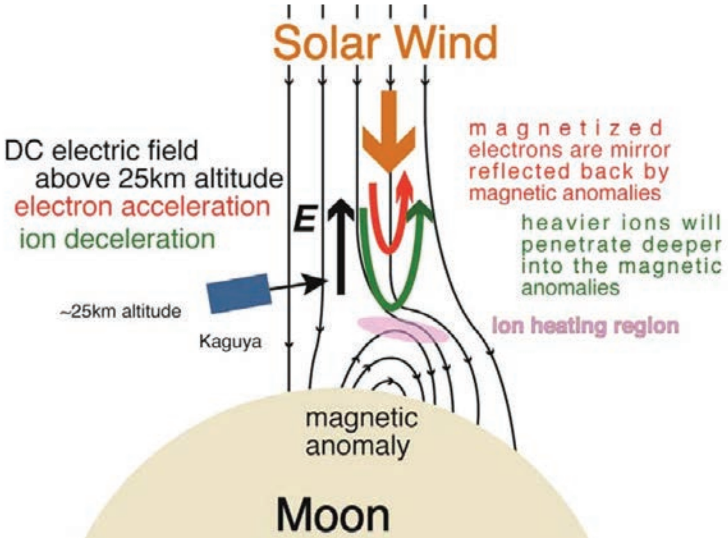

FIGURE B-25 A schematic of the physics related to the interaction of the solar wind with a lunar magnetic anomaly. The magnetic field of the anomaly is compressed by the dynamic pressure of the solar wind, which leads to an upward-pointing electric field. This decelerates the ions and reflects a fraction of them back upward into the solar wind prior to ever reaching the surface, and heats them. Reflected ions have been observed above these magnetic anomalies by the Kaguya spacecraft.
SOURCE: Saito et al. (2012), https://doi.org/10.5047/eps.2011.07.011. CC BY 4.0.

- *Plasma instabilities produced by wave-particle interactions:* Although the solar wind is primarily absorbed by the Moon, there is a long wake in the down-wind direction, forming a plasma cavity on the lunar dark side. Ions and electron beams can fill this region by moving along or across local turbulent fields, driving plasma instabilities. Meanwhile, on the sunward side of the Moon, electrons are lost in the local plasma distribution via absorption of solar wind electrons by the lunar regolith through a poorly understood process. The resulting anisotropic plasma distribution is another source of plasma instabilities in this region. The Moon is also a source of charged particles through either charge exchange processes near the surface, photoemission, secondary electrons, or reflection of particles by magnetic fields near the surface, which all contribute to a variety of plasma instabilities occurring over a broad range of frequencies. All of these processes can be simulated but are largely unexplored observationally.
- *Shocks and magnetic reconnection:* The interaction of the solar wind with magcons create shocks and are thus potential sites of magnetic reconnection, modified by the local plasma environment compared to reconnection occurring elsewhere in the heliosphere. Near the Moon's surface, electrons remain magnetized because of their small radius of gyration about the strong magnetic fields, while ions move with little deflection by the magnetic field owing to their much larger gyroradius. The physics of this interaction is analogous to the diffusion region in studies of magnetic reconnection. Moreover, the magnetic field geometry near the magcon can resemble that commonly associated with magnetic reconnection. As an example, just to the left of the "ion heating" region noted in Figure B-25, interplanetary magnetic field lines (not shown) may resemble a typical X-point pattern.

Much new insight can be gained through close study of the particle distributions and fields near the surface of the Moon and extending to a few hundreds of kilometers above it. At heights of about 100–200 km above the magcon, a bow shock may exist as the solar wind is slowed there, analogous to Earth's bow shock. The thickness of this shock is likely of the same order as the magcon itself. The interaction is almost certainly dynamic, owing to the different directions at which the solar wind arrives at the Moon and turbulent variations in its flux, and likely involves numerous smaller-scale shocks.

- *Dusty plasma environment:* Aside from the solar wind plasma, a variety of reflected ion and electron populations, and the presence of PUIs, there is also considerable dust in the exosphere of the Moon. Dust can be a major impediment to human and robotic activities on the lunar surface, and its distribution and transport near the Moon must be better understood. The Moon is an excellent laboratory for studying dusty, multicomponent plasmas. Hand-sketched drawings by Apollo-17 astronaut E.N. Cernan near the Moon revealed at least two separate components to the lunar dust environment that remain poorly understood. The large-scale hazy glow in these sketches is zodiacal light caused by the scattering of light off of interplanetary dust near the Sun, while the more streaky features are composed of exospheric dust near the lunar surface plus shadows from craters and light scattering off of lunar dust. The levitation of dust, caused by electric fields associated with solar UV and plasma interaction near the surface, and the transport of dust, is an important problem in the physics of dusty plasmas and a major challenge for deep space habitation.
- *High-energy particle radiation:* The surface of the Moon as well as the orbiting Gateway provide an important opportunity to make measurements of energetic particles over a critical energy gap from about 0.3–4 GeV between the high-energy end of SEPs and the low-energy end of GCRs. Currently, one instrument onboard the International Space Station (ISS) measures ions in this energy range, but the data are not readily available. Moreover, the ISS is in low Earth orbit, well inside Earth's magnetosphere. Cosmic ray instruments in cislunar orbit would be a major advance in the study of both GCR modulation by the Sun, and also the origin of intense, high-energy SEP events. This science is also critical with regards to human activity in space. While GCRs are at their lowest during solar maximum, unpredictable and hazardous SEP events occur regularly during solar maximum. Measurements of GCRs and SEPs from the cislunar region would address critical science questions concerning the transport and energy-dependence of GCRs as well as the acceleration of SEPs, and lunar samples may potentially provide historical records of significant past SEP events. Synergizing observations from Earth-based neutron monitors would further enhance their scientific return.

Heliophysics, Mars, and Planetary Sciences

Concurrent to the Artemis program, NASA has begun identifying the resources and technologies needed to enable Mars-forward missions through its Moon to Mars Architecture studies. The success of these truly deep space exploration missions will depend on a mature understanding of the radiation environment and space weather hazards to protect astronauts and technological resources en route to and at Mars. Identification and development of essential information and instrumentation during the Artemis era is a critical implementation need to add to and further enhance programs already in place, such as the Space Radiation Analysis Group that currently assesses astronaut exposure risk. Planning for and development of radiation and solar wind monitors as well as forecasting and nowcasting tools at Mars must begin within this decade.

In turn, heliophysics can leverage the enabling infrastructure (e.g., rideshares, operational resources) to not only support these missions (e.g., through solar wind and radiation measurements) but to also perform fundamental research in an accessible, interactive, deep space environment. Exploration near Mars and on the Martian surface provides exciting opportunities for synergistic scientific discoveries between the heliophysics and planetary sciences, including cosmic radiation impacts on planetary habitability in a thin atmosphere, solar wind and transient interaction with weak planetary magnetospheres, coupling between the solar wind and the Martian ionosphere, and solar influence on planetary surface composition.

Why Is This an Emerging Opportunity?

The renewed emphasis from NASA for human deep space exploration hastens the recognition of the Artemis and Moon to Mars programs as emerging opportunities for the heliophysics community. These programs are receiving unprecedented support for implementation by the U.S. government, international agencies, and commercial partners. Timing is critical for providing capability recommendations into the infrastructure as it is being designed and implemented by the participating agencies.

Leveraging the integrated capabilities of these deep space exploration programs integrates a broad list of research disciplines, including fundamental solar physics, magnetospheric and planetary science, space weather, space biology and life sciences, and human health. A wealth of science objectives are enabled by these emerging platforms through a shared need to understand, predict, and react to the dynamic interplanetary environment.

B.5 RESEARCH ACTIVITIES FOR THE DECADE

This section presents an ambitious research plan guided by the science goals and emerging opportunities identified by the SHP and described in the previous sections. Section B.5.1 outlines the degree to which current research activities can address these objectives and where gaps exist that need to be filled by new initiatives or upgrades to existing programs. Table B-5 further enumerates these gaps and summarizes the measurements needed to meet the PSG objectives and lists the capabilities needed to execute these measurements. Specific measurement requirements are intentionally absent from Table B-5, because the panel does not wish to be prescriptive and rather leave it to mission planners to specify requirements that best meet the science objectives. Section B.5.2 presents new space mission and ground facility concepts that the panel has determined best address the goals. Section B.5.3 discusses how these new missions and facilities, if realized, can be integrated into the HSO and presents additional considerations for how the HSO can be further upgraded to meet SH needs. Looking beyond new major facilities and space missions, it is important to consider how the rest of the SH research infrastructure must evolve to meet program goals. To that end, Section B.5.4 considers areas in which investment is needed to get the most out of new and existing programs.

B.5.1 Priority Science Goals—Capabilities, Opportunities, and Major Gaps

Priority Science Goal 1

Thanks to GONG, SOLIS, SOHO, and SDO, an invaluable synoptic set of observations of solar surface magnetism, solar plasma flows, and coronal evolution has been amassed. Synoptic full disk measurements have been supplemented by Hinode/SOT's high-resolution measurements of the solar magnetic field, which in the next decade will be significantly enhanced by Inouye. Rapid increases in high-performance computational power has led to a significant leap in the ability to simulate different aspects of solar magnetism and the solar cycle, including magnetohydrodynamic simulations that reproduce with remarkable fidelity surface magnetism observations, as well as simulations of the convective envelope that can reproduce solar-like, large-scale flow fields and oscillatory cycles.

The understanding of the solar dynamo and how it leads to the wide range of observed magnetic behavior critically requires the continuation of synoptic observation programs. It is vital that researchers retain the capability of making full-disk spectropolarimetry measurements that allow determination of solar magnetic fields and plasma flows. However, it has become clear that having observations limited to the Sun–Earth line represents an observational gap that must be closed during the coming decade. This gap has two main components: the lack of solar polar observations and the lack of solar far-side observations.

In the case of the solar poles, it has become increasingly evident that they play a central role in the long-term evolution of the solar dynamo. However, when it comes to modeling, the observational uncertainty associated with the solar poles prevents researchers from discriminating between models that have different behavior at high latitudes but otherwise match active longitude behavior equally well. Additionally, convective simulations hint at the possibility of using the poles as a diagnostic region that will help contextualize solar convection within that of other stars.

In the case of the solar far-side, the usefulness of the 360 degrees coverage enabled by the STEREO mission has already been seen, although limited only to the solar corona. Combining continuous 360 degrees spectropolarimetric measurements with coronal measurements would allow for better understanding of the process of emergence and evolution of active regions in a way that has never been possible. This will be particularly enlightening in the case of the largest active regions, which have lifetimes that can span several solar rotations.

TABLE B-5 Needed Capabilities to Advance the Sun and Heliosphere (Unranked) Priority Science Goals (PSGs)

Objectives	Requirements	Example Measurements	Needed Capabilities
PSG 1. How does the Sun maintain its magnetic activity globally from *pole to pole*?			
1.a. Determine the role of the polar and high latitude magnetic fields and flows in the evolution of the solar dynamo.	Vector observations of magnetic fields and flows in polar regions for at least 1 month on each pole at a 5-minute cadence (1.a, 1.b, 1.c)	Vector magnetic fields at high latitudes up to pole	Long-term (several months) spectropolarimetric observations of the polar regions
		Helioseismic measurement of flows at high latitudes	High resolution Doppler measurements
1.b. Determine how the dynamo-generated field emerges through the surface and shapes the 3D structure of the solar atmosphere and heliosphere.	Magnetic flux emergence processes and connection to global corona (1.a, 1.b, 1.c)	Latitude–longitude distribution of emergence	Global synchronous (front and back side) multiviewpoint magnetogram and doppler measurements
		Global magnetic structure of solar atmosphere	
		Multiviewpoint observations of surface	
1.c. Determine the nature of global flows and inertial waves at all latitudes, down to tachocline depth, and their relationship to the solar dynamo.	Helioseismic measurements of tachocline thickness, global flows, inertial waves at all latitudes and depths (1.a, 1.b, 1.c)	Latitude–longitude measurements of velocities and magnetic fields down to tachocline	Multiyear multiviewpoint doppler measurements including equatorial near-side, far-side, and polar regions
		Separate Rossby waves and inertial oscillations from convective motions	
1.d. Determine how solar magnetism changes over the solar cycle, from the solar interior, and through the highly coupled solar atmosphere.	Joint surface and helioseismic measurements. Modernize historical data to produce a long-term homogeneous observational baseline (1.a, 1.b, 1.c, 1.d)	Coordinated surface and helioseismic velocity measurements	Modernization, intercalibration, and homogenization of historical records, providing a multidecadal, multicycle observational set
		Long-term homogeneous records of fields, plage, coronal bright points, and coronal structure	
PSG 2. How do the Sun's magnetic fields and radiation environments *connect* throughout the heliosphere?			
2.a. Demonstrate how photospheric and chromospheric dynamics drive the corona.	Magnetic field strengths and topology in the solar atmosphere (2.a, 2.b, 2.c, 2.d)	Vector photospheric and chromospheric B field	High spatial resolution, high cadence optical and NIR imaging spectropolarimetry
		Vector coronal B field	Combination of radio, optical/IR, EUV spectropolarimetry
2.b. Determine the role quasi-steady processes play in the heating of the solar corona and the acceleration of the solar wind and nonthermal particles.	Photospheric drivers: power spectra of MHD waves, and tangling of field lines (2.a, 2.b, 2.d)	3D surface flows	High spatial resolution, high cadence optical imaging spectroscopy
	Thermal response of upper solar atmosphere (2.1, 2.b, 2.d)	Thermal plasma distribution and composition	*Remote:* high resolution, high cadence radio, optical/IR, EUV, and SXR imaging spectroscopy
2.c. Understand how the magnetic field of the corona and inner heliosphere is structured, how it evolves, and how it connects to and influences the interplanetary magnetic field on varying timescales.			*In situ:* multipoint, multiscale velocity vector, density, temperature measurements
	Spatial, temporal, and spectral distribution of energetic particles and their composition (2.b, 2.d)	Energetic electron distribution	*Remote:* high-dynamic-range radio and HXR imaging spectropolarimetry
			In situ: multipoint, multiscale electron spectral measurements

continued

TABLE B-5 Continued

Objectives	Requirements	Example Measurements	Needed Capabilities
2.d. Trace the origin of solar wind variability, and identify the extent to which it is owing to local kinetic processes or underlying global solar activity.		Energetic ion/neutron distribution and composition	*Remote:* sensitive gamma ray imaging spectroscopy *In situ:* multipoint, multiscale, multispecies electron/ion/neutron spectral measurements and composition
	Time varying and spatially distributed measurements of the heliospheric magnetic field. Distribution, dynamics, composition, and thermal properties of magnetized plasma (protons, alphas and heavy ions), suprathermal properties (2.b, 2.c, 2.d)	In situ magnetic fields, Properties of bulk solar wind plasma (electrons, protons, alphas and heavy ions), Suprathermal ion properties, Ion and element composition. Radio wave properties	*Remote:* EUV measurements, magnetograms, spectroscopy, coronal fields, heliospheric imaging *In situ:* multipoint, multiscale, multispecies electron/ion/neutron energy measurements, velocity distributions, composition, and in situ magnetic fields, radio waves.
PSG 3. How do solar explosions *unleash* their energy throughout the heliosphere?			
3.a. Determine how and where magnetic energy is stored and suddenly released, from kinetic to global scales, to drive solar transient events.	Vector magnetic field in the solar atmosphere before, during, and after the events (3.a, 3.b, 3.c, 3.d)	Vector photospheric magnetic field	High spatial resolution, high cadence optical imaging spectropolarimetry
		Vector chromospheric magnetic field	High spatial resolution, high cadence infrared imaging spectropolarimetry
3.b. Understand the dominant energy conversion and transport mechanisms that energize plasma and particles throughout the heliosphere.		Vector coronal magnetic field	Combination of radio, optical/IR, EUV spectropolarimetry
	Spatial, temporal, and spectral distribution of energetic particles and their composition (3.b, 3.c, 3.d)	Energetic electron distribution	*Remote:* high-dynamic-range radio and HXR imaging spectropolarimetry *In situ:* multipoint, multiscale electron spectral measurements
3.c. Measure and track the rapidly evolving properties of solar eruptions from the solar surface through interplanetary space.		Energetic ion/neutron distribution and composition	*Remote:* sensitive gamma ray imaging spectroscopy *In situ:* multipoint, multiscale, multispecies ion/neutron spectral measurements and composition
3.d. Improve methods for forecasting and nowcasting of solar eruptions at the Sun and for predicting the subsequent impacts on interplanetary radiation environments.	Distribution, dynamics, composition, and thermal properties of magnetized plasma (3.a, 3.b, 3.c, 3.d)	Thermal plasma kinetics, distribution and composition	*Remote:* high resolution, high cadence radio, optical/IR, EUV, and SXR imaging spectroscopy *In situ:* multipoint, multiscale velocity vector, density, temperature measurements for electrons, ions, including heavy ions
	Initiation, distribution, and evolution of shocks and waves (3.b, 3.c, 3.d)	Turbulence and waves	*Remote:* dm-m radio imaging spectroscopy, multi-LOS Faraday rotation observations

TABLE B-5 Continued

Objectives	Requirements	Example Measurements	Needed Capabilities
		Shock location, morphology, and strength	*Remote:* White-light coronagraph imaging from multiple perspectives *In situ:* multipoint, high-cadence measurements of B, n, T, v
PSG 4. How is our *home in the galaxy* sustained by the Sun and its interaction with the local interstellar medium?			
4.a. Ascertain the physical processes from the Sun to the LISM that shape the heliosphere and determine the spatial and temporal dependence of its boundaries. **4.b.** Establish how the dynamics and evolution of the global heliosphere are affected by solar activity, and by the LISM and its inhomogeneities. **4.c.** Determine how pickup ions are heated and accelerated across the termination shock, evolve in the heliosheath, and escape across the heliopause into the LISM. **4.d.** Infer how and where anomalous cosmic rays are accelerated, and how they and galactic cosmic rays are modulated by the Sun, heliosphere, and LISM.	Spatial structure and temporal variations of the heliosheath and LISM through remote sensing from inside and outside the heliosphere (4.a, 4.b)	ENA imaging of heliosheath and ribbon from a changing vantage point	ENA imager operating out to ≳100 AU beyond heliopause at energies from 1 to 100 keV
		Unraveling of processing and filtration of interstellar hydrogen, helium and other species by the heliosphere; properties of pristine interstellar neutrals	Neutral mass spectrometer operating from 3 AU (outside the H ionization cavity) to LISM
		Interstellar dust composition along outward trajectory from 1 AU to LISM	Interstellar dust analyzer operating from the inner heliosphere into the LISM
	The physical processes that form the Ribbon and determine its extent, shape, and temporal variability (4.a, 4.b)	ENA imaging from a changing vantage point	ENA imager operating out to ≳100 AU beyond heliopause at energies from 1 to 100 keV
		Ion, neutral and magnetic field observations through the ribbon	Neutral mass spectrometer, thermal and suprathermal plasma spectrometers, and fluxgate magnetometer operating along trajectory through heliosphere, heliosheath, and into LISM
	The complete ion distribution function at thermal, suprathermal and high energies, across the termination shock and throughout the heliosheath, and across the heliopause where they escape (4.a, 4.b, 4.c, 4.d)	Thermal, pick-up (suprathermal), and energetic ion distribution and composition, vector magnetic fields along outward trajectory from 1 AU to LISM	Ion and electron plasma spectrometers, suprathermal plasma spectrometer, energetic ion and electron telescopes, and fluxgate magnetometers operating along trajectory through heliosphere, heliosheath and into LISM
	Particle acceleration, energy dissipation, shocks and transients throughout heliosphere and LISM (4.a, 4.b, 4.c, 4.d)	Turbulence and wave-particle measurements along outward trajectory from 1 AU to LISM	Magnetometer and plasma wave probe, along with particle instruments, operating along trajectory throughout heliosphere, heliosheath, and into LISM
	Spatial and temporal variation of the spectra and anisotropy of galactic and anomalous cosmic rays, throughout the heliosphere and in the LISM (4.a,4.d)	GCR and ACR fluxes, spectra, composition and anisotropy into the LISM	Cosmic ray spectrometer with composition capability operating along trajectory throughout heliosphere, heliosheath, and into LISM

NOTES: These are capabilities that are either currently unavailable (or partially available) and need to be developed or are technologically ready but have not been implemented in this new context. Acronyms defined in Appendix H.

Having simultaneous coverage of the solar poles, far-side, and near side (i.e., 4π coverage) will give us an unprecedented perspective on the Sun as a global magnetic system, including the ability to perform a new generation of helioseismic inversions that will transform the ability to understand the 3D structure and variability of solar rotation, meridional circulation, and their role in driving the solar cycle. This, in combination with 4π magnetic and coronal measurements, will give insight into how kinetic energy is transformed into magnetic energy, as well as a complete picture of how this energy emerges into the solar photosphere and is subsequently released to shape the entire heliosphere. Importantly, 4π coverage will significantly improve our operational space weather capabilities, including the ability to forecast solar irradiance in advance, as well as have a complete understanding on the magnetic state of the corona that is currently impossible without knowledge of magnetic regions in the solar far-side. The panel refers the reader to the report by the Panel on Space Weather Science and Applications (see Appendix E) for more details.

Priority Science Goal 2

Detailed knowledge of dynamic processes over small scales in the solar atmosphere and of chromospheric magnetic fields are needed to fully understand the transfer of mass and energy in the solar atmosphere. The outstanding question of how the solar wind is heated and accelerated depends on this knowledge. PSP has discovered that interchange reconnection is the likely source of the fast solar wind inside of coronal holes. A combination of Alfvén waves and reconnection further heat and accelerate the solar wind. The mechanisms responsible for the slow solar wind remain unresolved but likely occur on small time and spatial scales and depend directly on the coronal magnetic field structure and dynamics.

In order to resolve these regions and their dynamics, new measurements of temperature, density, and composition are needed at high time cadence and high spatial resolution. The combination of recently operational, or near-future, facilities such as Inouye, SO, MUSE, and EUVST is poised to provide fundamentally new results on these topics by, for example, systematic studies of the dynamics of photospheric magnetic elements to obtain power spectra of MHD wave energy transport, coupled with measures of their photospheric field anchors as well as the associated coronal response, in particular the presence and amplitude of turbulent flows. Still needed are definitive and consistent measurements of the hottest coronal plasmas at dynamic and quiescent times, as well as nonthermal measurements. SXR and HXR spectral imaging of the corona, when combined with broad multiwavelength studies extending into the EUV, will reveal the degree to which coronal energization processes are impulsive versus steady. HXR and microwave measurements reveal the presence of any accelerated electrons, which is a direct probe of energization mechanisms. The astrophysical observatory, NuSTAR, combined with the Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket experiments have served as pathfinders in placing constraints on these processes. Going forward, solar-dedicated observatories with increased sensitivity across all of these wavelength regimes along with the capability of directly imaging HXRs will be necessary to fully measure the nonthermal contributions to the quiescent closed and open corona. These nonthermal assessments can be directly paired with in situ measurements in the middle corona and interplanetary space to study energization of the solar wind from its source. Still needed are definitive and consistent measurements of the hottest coronal plasmas at dynamic and quiescent times, as well as direct detection and measurements of nonthermal particles in extremely small energy release events.

In magnetically open regions, coronal spectroscopy will establish the link between remote sensing and in situ measurements, because it can fully characterize the plasma properties of the source region, to be compared with in situ wind measurements. Inouye, UCoMP, and other complementary techniques and instrumentation will advance the knowledge of strength and topology of the magnetic field in the chromosphere and corona, both at global and active region size, and provide new insight into how heating, acceleration, and expansion occur in the corona and inner heliosphere. Dedicated facilities that obtain synoptic, long-term, vector coronal magnetic field measurements will be necessary to understand how the global field relates to the evolving heliosphere at long (solar cycle) timescales. There is a need for instrumentation that can undertake high-resolution, off-limb spectroscopy to determine the temperature, density, and composition of the middle corona in order to fill in the observational gap in this region where almost all of the physical transitions and processes that control coronal outflow into the heliosphere occur.

As with PSG 1, a lack of observations of the polar regions of the Sun increases the uncertainty of behavior of the polar magnetic field, and subsequently the inner boundary conditions for solar and heliospheric models and reduces the ability to adequately describe the physics in these regions. Both high spatial resolution observations from the ground, and observations from outside the ecliptic plane, will be necessary to overcome these limitations.

It has become increasingly clear that single-point heliospheric observations are not sufficient to fully understand the origin, evolution, and propagation of the solar wind, and the connection from the Sun to the heliosphere. Connecting magnetic structures in the heliosphere back to their origin at the Sun requires disentangling complex magnetic field connectivity and time-varying fields and processes. Additionally, sparse heavy ion composition measurements limit the ability to trace heliospheric structures back to their sources, energization processes, energy partition, and release mechanisms. Connection science requires distributed measurements from constellation missions to track the evolution and physical processes occurring in the heliosphere that connect these phenomena back to the Sun. These measurements will better constrain model conditions at the Sun and in the heliosphere. It is equally important to support theory and model development, data analysis, and new mission development in order to move forward on this goal.

Priority Science Goal 3

Thanks to the successful operations of spacecraft including SDO/AIA, Hinode, RHESSI, IRIS, STEREO, and SO, and ground-based instruments such as EOVSA, DST, BBSO/GST, and CoMP, the previous decade has seen outstanding progress in realizing high-resolution imaging and/or spectroscopy of the Sun in a broad wavelength regime from radio to gamma rays. Together with in situ measurements of plasma and charged particles of various species in the near-Sun space and interplanetary space by PSP and SO, such capabilities have reshaped the understanding of solar explosive events. Recently operational or upcoming instruments such as Inouye, UCoMP, MUSE, EUVST, and potentially ECCCO (Phase A) are poised to further advance such studies in optical, IR, and EUV, and UV wavelengths, particularly for understanding the magnetized, multithermal plasma from the photosphere to corona. However, to unravel magnetic energy release, particle acceleration and transport in a much broader region, the next major breakthroughs call for next-generation instruments in radio and HXRs that can achieve imaging spectroscopy with a superior image dynamic range orders of magnitude better than currently available (extending the range from just a few times 10:1 to more than 1000:1) along with a high image fidelity. In HXRs, new instruments that employ direct focusing optics promise to achieve such a capability. In radio wavelengths, ground-based interferometric array concepts that can provide dense UV coverage would make key breakthroughs in a highly complementary wavelength regime. In addition, to better understand energetic ions, a highly sensitive gamma-ray instrument with imaging spectroscopy capabilities is required.

In order to systematically study the Sun's magnetic field before, during, and after eruptive events, it is required to derive the vector magnetic field at multiple altitudes and over a wide region, particularly in the corona where the energy release occurs, at a high enough cadence to capture the changes that lead up to and occur during the event. In the past decade, researchers have enjoyed detailed measurements of the photospheric vector magnetic field made by SDO/HMI and complemented by high-resolution measurements from BBSO/GST, Hinode, DST, and now Inouye. Upcoming instruments on space- and ground-based observatories, including the Chromosphere and Prominence Magnetometer (ChroMag) instrument of COSMO, SOLIS, and potentially CMEx (Phase A), are poised to greatly advance the measurements of vector field in the chromosphere. For measuring the coronal magnetic field, however, despite that initial breakthroughs have been made with EOVSA, CoMP and, very soon, Inouye's Cryogenic Near-IR Spectro-Polarimeter (Cryo-NIRSP) instrument, this capability is still very much in its infancy. To further advance the capabilities of measuring the coronal magnetic field over a broad region, significant development of instrumentation and methods across different wavelength regimes is required. As an example, advanced radio techniques can enable measurements of the rapidly varying coronal magnetic field in solar flares and CMEs from low to middle corona while offering new capabilities of measuring the coronal field in active regions and quiet Sun, both against the disk and off limb. Additional measurements to consider developing that target coronal magnetic field diagnostics include those that utilize recently identified magnetically sensitive EUV spectral lines or take advantage of either sensitive IR or UV polarimetry over the global corona. Such a crucial gap in the knowledge of the volumic coronal magnetic field from near the solar surface to the interplanetary space and the need to make progress on this ground are further tied to the LRG identified by the panel.

Over the past decade, observations of solar explosive events and energetic particles from multiple vantage points offered by, for example, STEREO, SO, and PSP in combination with Earth-based instruments, have provided unprecedented insights into the 3D structure and evolution of CMEs, the spread of solar energetic particles, and more. For a full understanding of how the Sun ejects the coronal plasma and energizes particles over the entire lifetime of an explosive event, and for greatly advancing the ability to predict space weather impacts, it is necessary to combine multiwavelength, multiperspective remote sensing observations of its source region and spatial-temporal evolution with in situ measurements of the resulting plasma and particles throughout the heliosphere. To make significant progress, multispacecraft constellations or networks of space- and ground-based telescopes with complementary instrumentation will be required.

Priority Science Goal 4

The previous decade has seen a remarkable maturation in the understanding of our home in the galaxy, and at the same time has exposed how much researchers still do not comprehend. The field is approaching a limit to what can be learned through in situ and remote sensing observations from 1 AU. The Voyagers, New Horizons, and IMAP will continue to provide discoveries, but to bring about a truly transformational leap in understanding of how the heliosphere is sustained by the Sun and the local interstellar medium requires a mission carrying a full complement of instruments targeted for direct exploration of the outer heliosphere and LISM—namely, an interstellar probe.

IBEX, the Voyagers, and advanced modeling have revealed much about the processes that shape the heliosphere and how heliosphere evolution is affected by solar activity and the LISM. In the near future, IMAP will enable new discoveries into spatial and temporal variations of the heliosphere caused by solar activity. IMAP will produce accurate high-resolution ENA spectra that can be used to infer the line-of-sight-integrated distribution of heliosheath ions. To press further, an interstellar probe measuring ENAs at a vantage point other than 1 AU would provide crucial new information. Additionally, in situ observations along trajectories other than those provided by the Voyagers will provide additional direct determinations of the locations of the TS and HP. A trajectory that transits through the IBEX Ribbon, believed to be located beyond the HP, will inform ion retention physics models needed to explain the existence of the Ribbon. The Voyagers will continue to measure disturbances and their effects on GCRs in the LISM. However, true advances in determining the origin and properties of these unusual structures will only be possible with the capabilities and longevity of an interstellar probe that can operate hundreds of astronomical units past the HP.

Voyager, IBEX, and New Horizons have shown that PUIs are the dominant particle population in the outer heliosphere and within the heliosheath. Thus, determining how PUIs are heated and accelerated is critical for understanding the physical processes that govern the heliosheath and the interface with the LISM. New Horizons will fill a major gap in the understanding of the plasma physics of the outer heliosphere by measuring interstellar PUIs at the TS and beyond. New Horizons will make the first measurements of the heating of PUIs across the TS, which will occur within the next decade. However, because New Horizons does not provide magnetic field measurements, and it will not likely survive to the HP, the picture will be incomplete until an interstellar probe journeys deep into the heliosheath, across the HP, and into the LISM.

With more capable interstellar neutral instrumentation than IBEX, as well as the ability to detect interstellar dust and measure the Ly-α helioglow, IMAP will markedly advance the knowledge of the LISM. However, from the vantage of 1 AU, only a heavily processed and filtrated remnant of the interstellar medium is observed, and involved, post-measurement analysis is required to infer LISM properties. In fact, the most abundant interstellar constituent, interstellar hydrogen, is nearly undetectable at 1 AU, as Earth is situated in a hydrogen ionization cavity that extends to ~3–5 AU. Because of their importance to the physics of the interaction between the Sun and LISM in creating the heliosphere, it is critical to accurately characterize the interstellar neutral population, including their density, velocity, temperature, and composition, on an outbound trajectory through the heliosphere and into the LISM itself.

Voyager and IBEX have provided intriguing findings about ACR acceleration and GCR modulation, such as ACRs may originate at the flanks of the heliosphere, and that the heliosheath and HP are very effective at modulating GCR intensities. An interstellar probe will measure the complete distribution function from thermal energies (~keV) to cosmic-ray energies (~100–300 MeV), as well as particle anisotropies. As an interstellar probe transits the heliosheath, HP, and LISM, these measurements will provide the needed measurements to determine the source of ACRs and to understand GCR modulation.

Longer-Range Goal

The longer-range goal (LRG) identified by the SHP focuses on the need to improve capabilities for measuring magnetic fields in the corona and in the IPM. Current measurements include spectropolarimetric coronal diagnostics provided by optical/IR instruments, such as UCoMP and Inouye, as well as radio observations from EOVSA. Magnetic fields in the IPM are observed directly by numerous spacecraft with magnetometers, principally ACE, Wind, STEREO, PSP, and SO.

It is still a long way from having routine coronal field data products that are analogous to the photospheric magnetograms that have for decades been commonly available from both ground- and space-based sources. Multiple observing approaches need to be explored in the near future (e.g., ground-based optical/IR spectropolarimetry, ground-based radio spectropolarimetry, space-based spectropolarimetry), in order to establish the best long-term activity for measuring coronal fields regularly with sufficiently high spatial and temporal resolution. In the IPM, there's benefit in moving beyond the analysis of fields measured only along single tracks provided by single spacecraft. The most obvious path forward involves future constellation mission concepts designed to allow multiple spacecraft to probe IPM structures. New observational radio capabilities could also be relevant, with radio Faraday rotation being the only known way to probe IPM fields with remote sensing.

Emerging Opportunity 1

Past and present observations of the Sun remain crucial for the understanding of how stellar activity (e.g., flares, CMEs, winds) can affect exoplanets orbiting other stars. The solar example is essential for interpreting observations of stellar activity, which generally lack the spatial resolution available in solar data. Still, the applicability of the solar example can be questionable in many instances. This problem is particularly acute in studying stellar winds and CMEs, as the ability to study winds and CMEs on stars remains very limited, using observational methodologies quite different from how the solar wind and solar CMEs are observed. Observational efforts made on both the solar and stellar sides may help bridge this gap. Importantly, because stellar winds shape the astrospheres of other stars, comparative studies between the heliosphere and other astrospheres can be used to back out the nature of stellar winds and magnetic fields. A critical asset in this regard will be an interstellar probe that directly samples the outer heliosphere and LISM, providing inputs into models of astrosphere/ISM interactions. Programmatically, cross-disciplinary studies involving heliophysicists, stellar astrophysicists, and planetary researchers would support further investigation.

Emerging Opportunity 2

Exploration is at the core of NASA's mission priorities. The current agency-led expedition program, Artemis, will establish lunar bases with a human presence in the next decade along with a lunar-orbiting station, Gateway, all with an eye toward sending humans to Mars. Inhabiting an environment unprotected from deep space radiation carries inherent risks to biology and infrastructure, creating a critical need for practical input from the SH communities regarding dynamic radiation environments (i.e., space weather). Meanwhile, these exploration programs are building infrastructure in previously inaccessible environments that can provide unique and exciting research opportunities in SH science, including the lunar bases, instrument platforms onboard or directed from Gateway, and a new communication network. These opportunities lend themselves to supporting a broad multidisciplinary portfolio and a range of instrumentation, similar to (but smaller than) what has been supported by the ISS. Time is of the essence for the NASA Heliophysics Division to become part of the Artemis and Moon to Mars infrastructure and mission strategy.

B.5.2 New Mission Concepts and Facilities

This section presents the strategic space mission and ground facility element of the SHP research activity. For the present decadal survey, the scientific community submitted several space-based mission and ground-based facility concepts addressing a diverse set of compelling science questions. The panel considered the degree to which these concepts addressed the SHP science goals and also their technological readiness. Of the 12 space mission concepts considered by the panel, five candidates were put forward to the steering committee for technical feasibility, risk, and cost review through the technical, risk, and cost evaluation (TRACE) process (see Appendix G). The candidates were derived from the community input paper concepts but are not necessarily identical to them and often reflect a combination of those papers. To underline this mission concept construction process, the names assigned to the candidates are intentionally generic in nature so as not to imply endorsement of any one particular community input paper concept. The SHP also reviewed multiple community input papers proposing new ground-based facilities, and based on these and inputs from other sources, selected three facilities that most effectively address the SH science goals (FASR, Next Generation Global Oscillations Network Group [ngGONG], and COSMO) for consideration by the steering committee.

Figure B-26 presents a matrix illustrating how the capabilities of each of the selected space mission and ground facility concepts will address the SHP's (unranked) PSGs and associated objectives. Each concept is rated by the degree to which it contributes to the specific goals and objectives. Note that implementation of the entire program would make major advances in all SH goals.

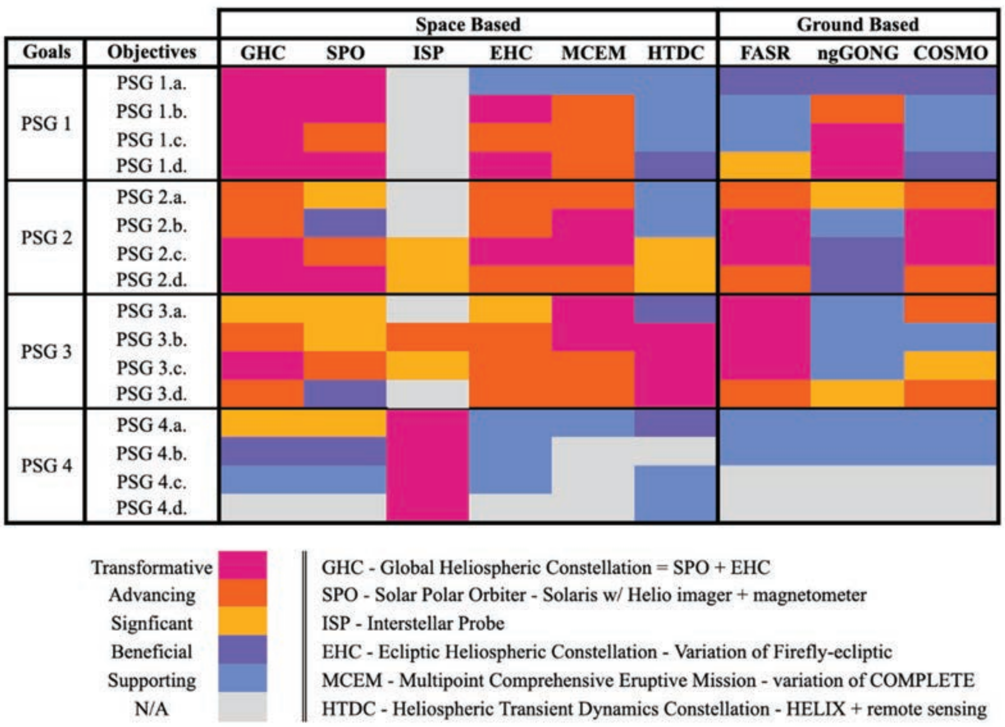

FIGURE B-26 Rating matrix of contributions of the Panel on the Physics of the Sun and Heliosphere's proposed mission concept and facility capabilities to the Sun and heliosphere priority science goals (PSGs) and objectives.
NOTE: Acronyms defined in Appendix H.

Space-Based Mission Concepts

Global Heliospheric Constellation

Owing to PSP, SO, STEREO, SDO, and the other elements of the HSO, fantastic progress has been made in the past decade to advance understanding of the global structure and dynamics of the Sun and inner heliosphere. To make the next big leap in the understanding of the solar dynamo, the origin of the solar cycle, causes of solar activity, and how the heliosphere is generated and evolves, will require long-term simultaneous observations of the Sun and heliosphere from multiple vantages, including the solar poles. The GHC concept takes a holistic observational strategy by placing a constellation of spacecraft around the Sun to make both remote sensing and in situ observations of the Sun and heliosphere with nearly 4π-steradian coverage. GHC consists of an SPO plus an Ecliptic Heliospheric Constellation (EHC). The single SPO spacecraft would nominally achieve a solar latitude of ~75 degrees or more. In conjunction, the EHC spacecraft, located at 1 AU, would be distributed at three locations—namely, one at Earth and two parked between 90 degrees and 120 degrees from the Sun–Earth line (one ahead of Earth and one behind). The combined science capability from having full longitudinal coverage in the ecliptic and from multiple long-duration (>3 months) polar passes will truly escalate the understanding of the Sun–heliosphere system. GHC carries out ground-breaking science across three of the panel goals: PSGs 1–3.

The panel recognizes the ambitious nature of GHC and therefore has divided GHC into the two distinct mission elements, SPO and EHC, so that they could be independently evaluated in the TRACE process in the event that programmatic needs require a staged execution. These elements are described in greater detail in the next two sections. Although presented as standalone mission concepts, the “whole is greater than the sum of its parts,” and the most impactful progress is made through the execution of the full GHC concept, as indicated in Figure B-26.

Solar Polar Orbiter: The Sun’s poles are the last unexplored frontier of the inner heliosphere. In recent years, researchers have come to realize that achieving science closure in solar physics will require direct observation of the solar polar regions, hence the single-most impactful solar mission of the next decade is a solar polar mission. SPO addresses fundamental unanswered questions such as: How does the solar dynamo generate cycling magnetic fields? How does it drive solar activity and shape the heliosphere over the solar cycle? Polar vector magnetograph observations provide insight into these questions by probing the nature of deep convection, which drives the solar dynamo engine and ultimately shapes the solar cycle. A mission to the solar poles is at heart one of discovery: There are no measurements of how differential rotation behaves at the poles—Do the poles spin up or spin down? What does convection look like at the poles? Are there complex polar vortex flows like those discovered on Jupiter and Saturn? Are there meridional countercirculation cells? What is the strength of the polar magnetic flux? Is there enough to resolve the “open-flux problem?”

The polar vantage provided by SPO also reveals a unique, new view of the corona and heliosphere. It will resolve the longitudinal structure of the streamer belt, as well as the longitudinal and radial evolution of transients and CIRs in the ecliptic plane. Combined with in situ plasma and energetic particle measurements, SPO will investigate the latitude variation of the steady-state and dynamic connections between the Sun and heliosphere. Ulysses revealed the unexpected nature of the high-latitude solar wind, but without any solar imaging instrumentation, the understanding of how polar coronal structure and dynamics map into the heliosphere is profoundly incomplete. Soon, SO will fly up to 30 degrees latitude, but this will only provide glimpses of the solar polar regions and will not allow for multimonth monitoring of the polar flows needed for helioseismology, and SO will not enter into the steady high-speed stream flow present during solar minimum.

SPO finally makes the connections between the properties of the high-latitude solar wind plasma and composition as well as energetic particles and the solar source. Indeed, SPO will transformationally inform all of the science objectives of PSG 1 and make significant contributions to many of those of PSGs 2 and 3. Summarizing the key science objectives of SPO:

- Understand how polar magnetic fields and flows are connected to the Sun’s global dynamics and the mechanisms that drive the solar dynamo, which ultimately shape the solar activity cycle.
- Determine how high-latitude coronal magnetic field topology connects the Sun and heliosphere throughout the solar cycle.

- Determine how coronal longitudinal structure and dynamics shapes the solar wind throughout the solar cycle.
- Understand the sources and transport from equator to pole of energetic particles through the inner heliosphere.

The surveyed SPO concept provides the needed observations through multiple polar passes (~12 in a 10-year primary mission; 6 in a 5-year extended mission) lasting more than 100 days on average (see Figure B-27) over the course of a decade to cover a full solar cycle. A Jupiter gravity assist would place SPO into a polar orbit, and an Earth gravity assist would be used to reduce the aphelion and to circularize the orbit to a ~3-year period (a Venus gravity assist is another option).

Ecliptic Heliospheric Constellation: The EHC addresses many of the same science questions as the SPO, but in a complementary manner. EHC provides continuous observations of the solar surface with unprecedented coverage on account of its complete long-term 360 degrees longitudinal coverage of the solar surface. This coverage provides critical observational capabilities to address questions impossible to answer from a single viewpoint, or from only brief happenstance distributions of multiple spacecraft.

For helioseismology, EHC enables a three-fold increase in observational depth, owing to the fact that the depth to which the solar interior can be probed scales with the horizontal distance over which the measurements are taken. This delving will provide new knowledge of critical regions like the tachocline, the structure and shape of which plays crucial roles in determining global distributions of active regions. Long, synchronous observations by EHC over all longitudes (1) enable determination of the number of meridional cells with latitude and depth; (2) remove mode degeneracies, resolving controversies about subsurface structures; and (3) determine the roles Rossby waves and other inertial waves play in driving the 3D dynamo and longitude-dependent solar cycle features. EHC solar far-side observations will be used to validate helioseismic holography, a promising technique in ground-based helioseismology (e.g., a future ngGONG network) for viewing far-side solar activity for decades into the future. This technique can be extended to develop asteroseismic holography to track far-side activity on other stars.

EHC provides full longitudinal continuity to follow the evolution of magnetic structures and the buildup of energy in the solar corona. Such comprehensive surveillance enables the discovery of the physical processes leading

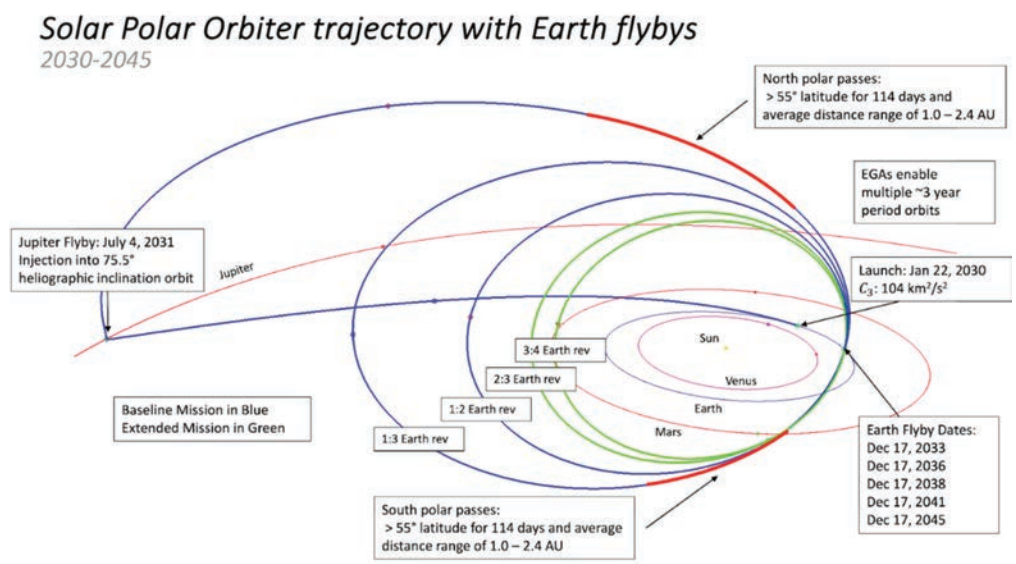

FIGURE B-27 The Solar Polar Orbiter mission concept considered in the technical, risk, and cost evaluation (TRACE) review, assuming a January 2030 launch.
SOURCE: Adapted from TRACE trajectory analysis provided by The Aerospace Corporation.

to the formation of complex sunspot active regions and filaments prone to eruption and advances the understanding of long-range interactions leading to sympathetic eruptions. Currently, it is not possible to consistently track the evolution of active regions as they rotate to the solar far-side or detect the emergence of new far-side active regions, greatly hindering the ability to forecast solar eruptions. EHC's full longitudinal coverage allows us to build much more accurate synoptic maps of the photospheric magnetic field that are used as the boundary conditions for global coronal and MHD solar wind models. More complete input boundary conditions, along with improved measurements of the longitudinal evolution of solar wind structure through EHC's in situ plasma and composition measurements, enables a leap in accuracy of solar wind models that in turn will have a transformative impact on the building of space weather forecasting capability.

EHC's simultaneous viewing from multiple vantages enables stereoscopic observations of atmospheric features like coronal loops and CMEs, overcoming the complications of 3D reconstruction from 2D plane-of-sky projected observations. Multiple viewpoints also allow for better determination of the vector field at the photosphere (i.e., azimuth disambiguation). Importantly, the long duration of the EHC mission and its stable orbital configuration will provide the continuity needed to capture many more such events than STEREO.

In summary, as a standalone mission concept, EHC will have a transformative impact on most of the science objectives of PSG 1 and many of those of PSGs 2 and 3. The baseline science mission, to cover most of a solar cycle, is 10 years. Summarizing the key science objectives of EHC:

- Understand the role of surface and subsurface flows and toroidal magnetic field instabilities in producing the cyclic solar dynamo.
- Understand the conditions that precipitate solar explosive activity and the role of magnetic field connections across large scales.
- Determine how conditions in the solar wind vary with longitude in response to changing global solar conditions over the course of the solar cycle.

GHC instrumentation and descope considerations: The SPO spacecraft and the two EHC ecliptic orbit spacecraft (EHC-ecliptic) ideally have the following instrument suites (all based on instrumentation with high technological readiness):

- *Doppler vector magnetograph*—dopplergrams with 3+ month high-latitude continuity and magnetograms to quantify polar magnetic flux along with continuous ecliptic coverage
- *EUV imager*—EUV images out to 3 solar radii
- *White-light coronagraph*—view of extended corona
- *Heliospheric imager*—longitudinal views of transients from polar vantage
- *Magnetometer*—in situ vector magnetic fields
- *Ion–electron spectrometer*—solar wind proton and electron speed, density, and temperature
- *Ion mass spectrometer*—composition and kinetic properties of solar wind heavy ions
- *Energetic particle suite*—electrons—0.01–10 MeV, ions: 0.01–300 MeV/nuc

The EHC Earth-orbiting spacecraft (EHC-Geostationary [GEO]) has only the remote sensing instrumentation listed above. This spacecraft is included as part of the baseline EHC concept on account of the aging of SDO, which has already experienced significant instrument degradation. EHC-GEO has similar capability to SDO but with more streamlined and compact instrumentation. No in situ package is included on EHC-GEO, as it is assumed that IMAP will provide the necessary in situ measurements.

In terms of descope options, as mentioned above, the single-most compelling element of the GHC mission is the SPO. If budget considerations do not allow for the full constellation, then a staged approach could be considered, first flying the polar component as a stand-alone mission, and flying EHC at a later time. That said, the overall science impact of GHC would be markedly increased with significant temporal overlap between the SPO and EHC operational phases. An alternative means of reducing EHC cost would be to not include EHC-GEO. This descope would only be sensible if NASA decides to replace the capability of SDO by other means.

An Interstellar Probe

Scientists are only beginning to understand the evolutionary path of the heliosphere through the galaxy and how the Sun produces and maintains the vast heliosphere. It is now understood that the heliosphere dramatically changes over time, as it passes through galactic clouds or is impacted by shock waves from nearby supernovae. Indeed, even over the course of a solar cycle, it has been learned from IBEX that the heliosphere is highly dynamic and keenly sensitive to the properties of the outflowing solar wind. IBEX will soon be followed by IMAP, which will carry out even higher fidelity remote observations of the heliosheath. But only through the direct measurement of the plasma and gas interactions that span the reaches from Earth into the LISM will researchers be able to unravel the interactions that uphold and drive the heliosphere. An interstellar probe will surpass the legacy of Voyager and New Horizons of direct in situ measurements of the outer heliosphere and beyond by being fully instrumented for focused study of the heliosphere and VLISM. With an interstellar probe, all of the target science objectives of PSG 4 are addressed by undertaking a journey to interstellar space with a focused mission to understand our home in the galaxy (see Interstellar Probe Mission Concept Study Report; NASA [2021]).

An interstellar probe would transect the heliosphere from one to several hundreds of astronomical units with a comprehensive suite of state-of-the-art instrumentation to make critical observations to answer these fundamental questions:

- How is the heliosphere upheld by the physical processes from the Sun to the VLISM?
- How do the Sun's activity and the interstellar medium, with its possible inhomogeneity, influence the dynamics and evolution of the global heliosphere?
- How do the current VLISM properties inform the understanding of the evolutionary path of the heliosphere?

To answer these questions, the Interstellar Probe concept is a spin-stabilized spacecraft hosting a full complement of in situ instruments that make charged-particle measurements covering the full energy range of a few electronvolts to gigaelectronvolts, ensuring there are no energy gaps. Equally important are observations of interstellar neutrals and dust along with the remote sensing of heliospheric ENAs and Lyman-α. All instruments in the notional payload are at a high level of technological readiness. The primary science phase lasts 50 years, beginning right after commissioning, broken into three mission phases (Figure B-28): The heliosphere phase targets the detailed evolution of the solar wind and its transients, and the growing dominance of PUIs in carrying the internal energy of the flow. Remote ENA and Lyman-α imaging will provide a "movie" of the heliosphere from a changing vantage point, reaching the TS after about 12 years, or a full solar cycle. The heliosheath phase explores the heliosheath over ~5 years, measuring for the first time suprathermal ions that dominate the bulk plasma dynamics. The interstellar phase begins after crossing the HP with continuous in situ measurements and remote ENA and Lyman-α images looking back at the heliosphere, giving us the first view of our home from the "outside."

Specific science objectives, all strongly tied to PSG 4, span investigations related to fundamental properties of the solar wind beyond 1 AU to the nature of the pristine ISM:

- Resolve the birth and evolution of interstellar and inner-source PUIs.
- Determine the physical processes that control the extent and shape of the IBEX Ribbon and belt.
- Determine particle acceleration mechanisms occurring at the TS and particle evolution across the heliosheath that uphold the force balance and their global manifestations.
- Characterize the nature and structure of the heliospheric boundary and how it is modified by solar dynamics.
- Determine the properties and inhomogeneity of the VLISM and the extent and impact of solar disturbances.
- Determine the sources and dominant acceleration mechanisms of ACRs.
- Constrain the origin of GCRs and characterize how GCR intensities are modulated by variations in heliosheath properties.

The baseline mission design calls for a 2036 launch by a Space Launch System (SLS) Block 2 and a Jupiter gravity assist to achieve an exit velocity of 7.0 AU/year. The target exit trajectory is 80 degrees from the nose, toward 180 degrees ecliptic longitude and –20 degrees ecliptic latitude transecting the heliosphere in an unexplored

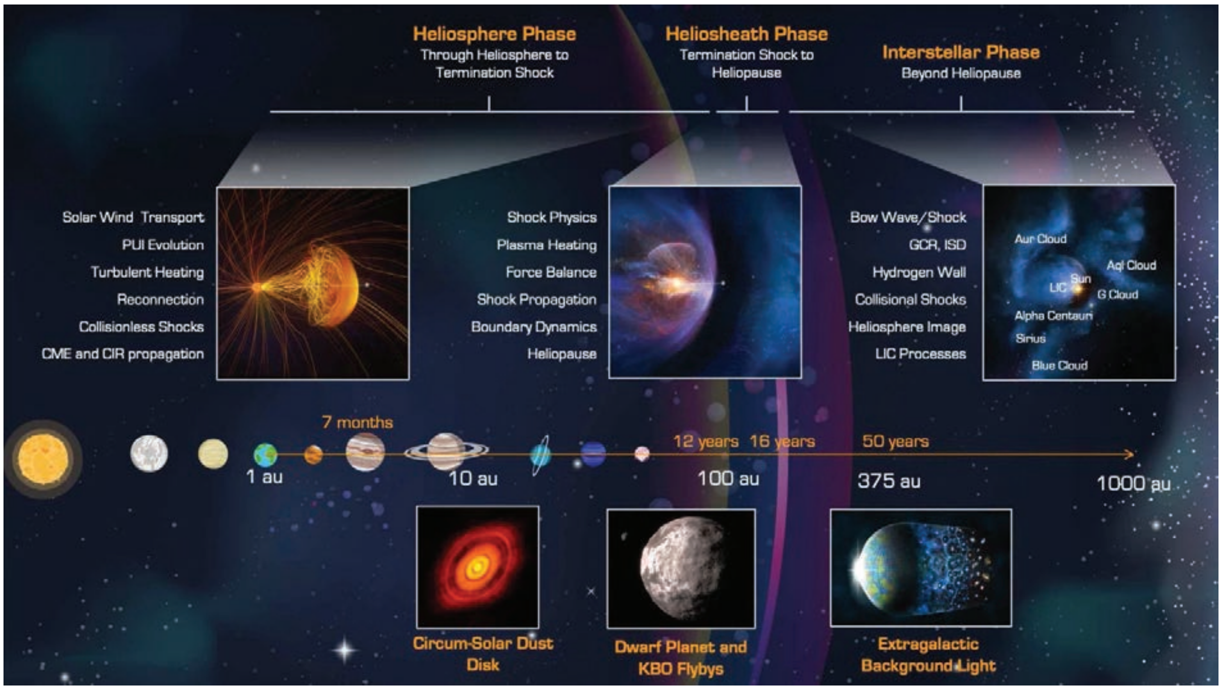

FIGURE B-28 The Interstellar Probe prime mission would last 50 years and is divided into three phases: heliosphere, heliosheath, and interstellar. Understanding the heliosphere and its home in the galaxy requires science observations starting near the Sun and out through the heliospheric boundary and ultimately out into the unexplored local interstellar medium. Interstellar Probe would span a broad range of solar and space physics domains and offer natural opportunities for astrophysics and planetary science investigations.
NOTE: Acronyms defined in Appendix H.
SOURCE: Brandt et al. (2023), https://doi.org/10.1007/s11214-022-00943-x. CC BY 4.0.

direction, intersecting the IBEX Ribbon and offering a scientifically compelling external side-view ENA image. Because of the long duration of the mission, a robust mission longevity design is planned, including system redundancy, a long-duration parts reliability testing program, and plans for maintaining the flight system, ground infrastructure, and mission staffing for 50 years of operation.

If future science budgets allow, an augmented mission adds planetary science and astrophysics goals “Understand the origin and evolution of planetary systems” and “Explore the universe beyond our circumsolar dust cloud,” enabled by removal of the Lyman-α imager and the addition of a visible-IR mapper for geological and compositional analysis of dwarf planets, and an IR mapper optimized for astrophysics investigations. An augmented mission is highly strategic by making Interstellar Probe truly cross-divisional, allowing for cost-effective combining of resources across NASA Heliophysics, Planetary Science, and Astrophysics. The inclusion of international partners leverages common science objectives. Strong interest has been expressed by European partners in contributing substantially to Interstellar Probe, both with science instrumentation and European deep space communication assets (Wimmer-Schweingruber et al. 2022). Indeed, an additional science objective, to test the Law of Universal Gravitation at 100 AU scales via use of the radio communication system, has been proposed by European contributors.

If, on the other hand, budget demands require descoping, substantial savings may be realized by use of a less powerful non-SLS heavy launch vehicle. This vehicle change results in a lower exit velocity—for example, a Falcon Heavy launch yields a speed of 5.2 AU/year, increasing the time to the TS from 12 to 16 years, and the heliosheath crossing time from 5 to 7 years. Although a delay in arrival at the TS is not ideal, arguably a longer heliosheath passage allows for more time to achieve heliosheath science objectives. Another trade to consider is reducing the primary mission duration, and hence reducing the demands on parts longevity certification. The baseline duration of the interstellar phase is 33 years (to reach 350 AU at 7 AU/year). The design lifetime could be scaled back to, say, 30 years to 200 AU, with an extended mission to 350 AU (albeit at higher longevity risk).

Multipoint Comprehensive Eruptive Mission

The Multipoint Comprehensive Eruptive Mission (MCEM) concept aims to understand the causal links between the Sun's evolving 3D magnetic field and many forms of energy release and transport in the corona, and includes the following science goals:

- Understand the global magnetic energy storage available prior to an impulsive event and how it transforms during sudden energy release.
- Understand the magnetic drivers of coronal heating and the solar wind.
- Determine the scaling laws associated with eruptive energy release.
- Construct a globally coherent picture of solar energetic particle sources and subsequent impacts of their acceleration through the heliosphere.

MCEM includes two spacecraft at L1 and one at L4, each with a set of instruments chosen to maximize the benefit of the multiviewpoint measurement for studying energy release in solar eruptions. As a baseline, the primary L1 spacecraft includes heritage instrumentation consisting of a photospheric magnetograph, an EUV filtergram imager, SXR and HXR spectroscopic imagers, and an ENA spectroscopic imager. Optimally, an instrument capable of directly measuring coronal magnetic fields would be included at L1, possibly also at L4. However, such space-based technology has not yet been demonstrated for coronal applications at a cadence commensurate with eruptive events, although its development is of such importance that it has been highlighted as the SHP LRG. Also at L1, but on a separate spacecraft owing to its size, is a gamma-ray spectroscopic imager for studying ions accelerated at the Sun. The L4 spacecraft includes a photospheric magnetograph, essential for obtaining source region magnetic fields at the limb.

With this arrangement, the L1 instruments provide unprecedented insight into high-energy particles and plasma at the Sun in eruptive events. The HXR instrument directly probes the locations, timing, and energetics of accelerated electrons, while the gamma-ray and ENA instruments provide the same for accelerated ions. The SXR and EUV instruments provide measurements of flare-heated plasma. The two photospheric magnetographs (with different viewpoints) ensure that the vector photospheric magnetic field is unambiguous, allowing for magnetic field extrapolation from the photosphere, ideally to be combined with coronal field measurements.

Many individual elements on the MCEM concept provide unprecedented capabilities for observing high-energy phenomena but are based on a history of development through smaller (in some cases, suborbital) missions. For example, the use of focusing optics for the HXR instrument (through the sounding rocket program), rather than the indirect imaging of past HXR missions, provides orders of magnitude increased sensitivity and, critically, the ability to measure flare-accelerated electrons directly at their acceleration sites in the solar atmosphere. Advances in gamma-ray imaging (through the balloon program) enable the dawn of a new capability for solar observations. Spectroscopic SXR imaging is also demonstrating rapid technological advancements (through the sounding rocket and CubeSat programs), promising to provide a definitive opportunity to distinguish the drivers of active region and flare heating.

While these instruments individually carry the promise of significant advances in the understanding of flare-related events, utilizing them as a single coordinated observatory enables a necessary coherent understanding of fundamental high-energy processes in the solar atmosphere (e.g., see Figure B-29). Integral to the MCEM concept is the co-analysis of data from all the instruments. Toward this effort, all instruments would produce data that is designed to be co-analyzed together. This concept includes a robust spatio-temporal modeling element that will be a standard part of data analysis. When MCEM observes a large eruptive event at the limb (e.g., the famous 2017 September 10 X-class flare), precise measurements will be made of all sources of accelerated particles and heated plasma with simultaneous magnetic field measurements. This stereoscopic view allows for the synchronous study of coronal dynamics and related photospheric impacts.

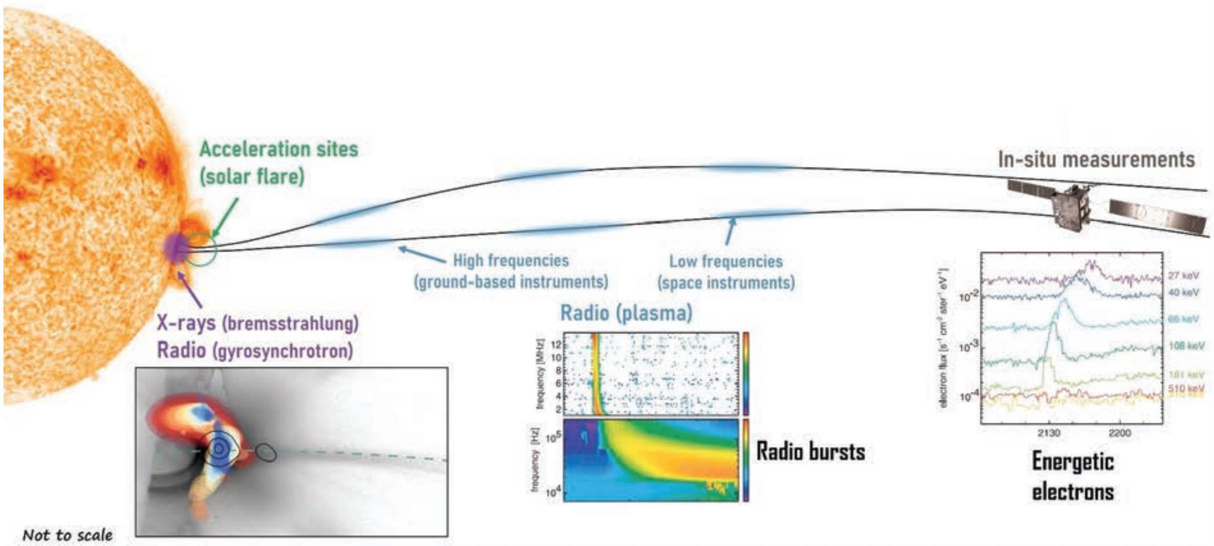

FIGURE B-29 High-energy observations are foundational for probing the sources and subsequent evolution of energetic phenomena at the Sun and throughout the heliosphere, including drivers of coronal heating, accelerated particles, flares, eruptions, jets, and the solar wind. X-ray measurements are the cornerstone of such observations, particularly for tracking particle acceleration. A coherent reconstruction of these processes would make great strides with complementary extreme ultraviolet and radio plasma diagnostics along with three-dimensional magnetic field measurements.
SOURCE: Glesener (2023), https://doi.org/10.3847/25c2cfeb.78fa7c49. CC BY 4.0.

While nearly all of the mission concepts surveyed by the panel stressed the capacity of the Deep Space Network and related resources, the MCEM concept is particularly telemetry intensive. For the full multipoint complement of spacecraft to achieve maximal success, optical communications need to be fully realized and implemented.

Heliospheric Dynamics Transient Constellation

The Heliospheric Dynamics Transient Constellation (HDTC) mission concept involves the launch of a constellation of spacecraft to study large-scale structures in the inner heliosphere, particularly ICMEs. Much of what is known about the plasma and field properties of ICMEs comes from spacecraft that encounter them, but there are limitations to how much can be learned about global ICME morphology from a single spacecraft track through such a large structure. Future progress toward understanding ICMEs, and how they evolve as they move away from the Sun, requires being able to measure their properties in detail at multiple points, and at different distances from the Sun. There have been cases in the past where ICMEs have encountered more than one spacecraft, but those instances are relatively few, as they rely on fortuitous alignments of spacecraft with different mission goals and instrument complements. HDTC would be the first mission explicitly designed to provide sampling of ICME structure at multiple locations (Figure B-30).

The version of the HDTC concept considered by the panel involves seven spacecraft with identical complements of instruments for measuring plasma and field properties. This suite includes magnetometers, solar wind plasma and composition instrumentation, suprathermal ion and SEP detectors, a solar wind electron detector, and an instrument for studying radio waves. Each spacecraft would also carry a single remote sensing instrument to complement the in situ measurements. Three spacecraft would carry photospheric magnetographs to ensure knowledge of the field topology underlying the ICMEs observed by the mission, even if they happen to erupt on the far-side of the Sun where Earth-based assets are not observing. For similar reasons, one spacecraft would carry an EUV imager. The remaining three spacecraft would carry heliospheric white-light imagers that could image the ICMEs in the inner heliosphere. In many cases, these imagers could image ICMEs as they pass over other spacecraft in the constellation, allowing connections to be made between ICME structures observed in situ and those seen in the images.

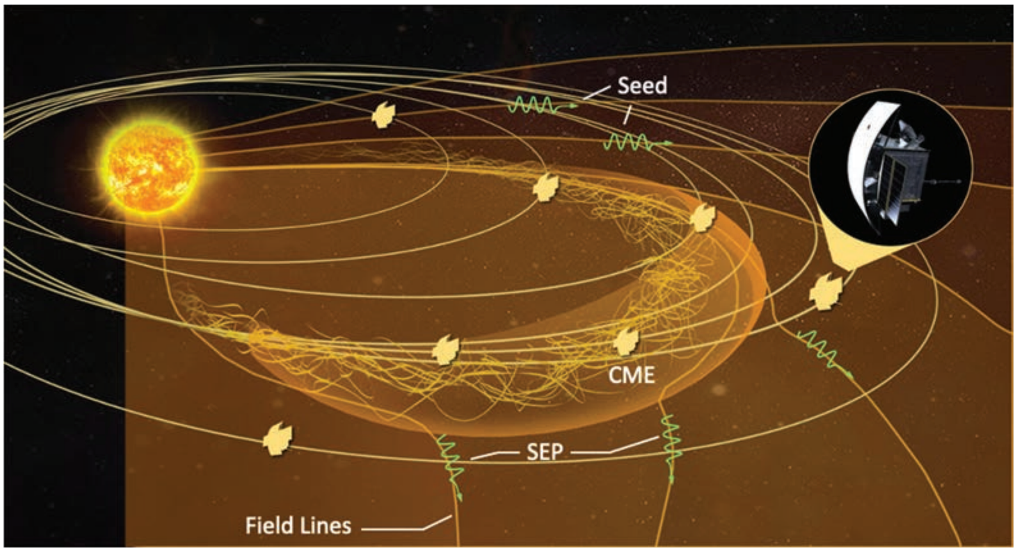

FIGURE B-30 An interplanetary coronal mass ejection (ICME) overtakes the seven spacecraft of the Heliospheric Dynamics Transient Constellation (HDTC) constellation. In order to determine the inner heliospheric structure and evolution of ICMEs, multipoint, in situ measurements of the magnetic field and solar wind plasma properties are necessary.
SOURCE: Szabo et al. (2022), https://doi.org/10.3847/25c2cfeb.7fb78e78. CC BY 4.0.

The HDTC spacecraft would be launched toward Venus, with a single Venus encounter placing the spacecraft into different final elliptical orbits with distances from the Sun typically ranging between 0.4–0.9 AU. The goal of the final orbital configuration is to have four to six spacecraft within 90 degrees of each other at all times, in order to provide proper sampling of ICMEs that happen to hit the constellation. Such unprecedented sampling of ICME structure would test theoretical understanding of underlying ICME magnetic morphology. Radial alignments of spacecraft would allow an assessment of the degree to which ICMEs can become distorted by their interactions with the ambient solar wind, and with other ICMEs. The EUV imager and photospheric magnetograms provide an essential connection to the ICME source regions. These multipoint observations would allow an exploration of how SEPs are accelerated and transported from their origins along ICME shocks. The data from these spacecraft would represent a valuable contribution to the HSO concept, and as a step toward an interplanetary field monitoring capability, it contributes to the SH LRG. Last, the mission could be a pathfinder toward a future operational space weather constellation focused on monitoring the Sun–Earth line.

The science objectives addressed by the HDTC mission concept significantly contribute to PSGs 2 and 3 and include:

- Use multipoint probing of ICMEs to provide stringent tests of models for ICME structure, particularly the magnetic flux rope paradigm.
- Probe ICMEs at different distances from the Sun to ascertain how ICME structures change during travel through the interplanetary medium, and how this might affect geoeffectiveness when directed toward Earth.
- Use multipoint sampling along interplanetary shocks to provide stringent tests of models for energetic particle acceleration and transport.
- Study the global structure of quiescent solar wind structures such as CIRs and SIRs.

All instruments have heritage and are technologically ready. The design concept has natural descope options, if necessary. The mission science goals are addressed most directly by the in situ measurements, so some or all of the remote sensing instruments could be removed. Indeed, the remote sensing requirements would be essentially obviated if the GHC/EHC mission proceeds. The number of spacecraft could also be reduced by one without a dramatic decrease in the percentage of time that there are 4 spacecraft within the desired 90 degrees.

Ground-Based Facilities

Frequency Agile Solar Radiotelescope

Solar radio emission provides unique and powerful diagnostics for a variety of physical processes in both the quiescent and active Sun. This fortuitous result is owing to a number of distinct emission mechanisms that operate at radio wavelengths that probe thermal plasma, nonthermal electrons, coronal magnetic fields, shocks, and waves. FASR is a next-generation solar-dedicated radio telescope that will bring exciting and transformative advances to several targeted objectives relevant to solar and heliophysics (namely, PSGs 1–3), which include:

- Making quantitative measurements of coronal magnetic fields in solar active regions/quiescent coronal cavities and their evolution before, during, and after solar flares and CMEs.
- Quantifying magnetic energy release and conversion in solar flares and, by measuring the spatial and temporal evolution of the energetic electron distribution in a broad flare region, providing fundamental constraints for electron acceleration and transport mechanisms.
- Providing near-real-time observations of CMEs from the low to the middle corona as well as associated shocks, which are major drivers for SEPs. Monitoring other key space weather drivers including intense solar radio bursts and F10.7 sources.
- Sharpening understanding of coronal heating and solar wind acceleration by detecting and quantifying thermal and nonthermal components of extremely weak energy release events throughout the quiescent solar atmosphere.
- Constraining the temperature, density, magnetic structure, and dynamics of the quiescent and active solar atmosphere in multiple layers from the chromosphere all the way to the middle corona.

In the past decade, thanks to the dedication of new instrumentation, solar radio astronomy enjoyed a significant advance from imaging at sparse frequencies or total-power dynamic spectroscopy to true imaging spectroscopy. In particular, as a pathfinder for FASR, EOVSA—consisting of 13 antennas working from 1–18 GHz—has made breakthroughs in measuring the dynamically evolving coronal magnetic field and the distribution of energetic electrons in the energy release region of solar flares. FASR is poised to make the next giant leap in several key SH objectives with its superior capability of broadband dynamic imaging spectropolarimetry, enabling entirely new insights into fundamental processes. FASR will produce a polarized spectrum along every line of sight toward the Sun at high time and angular resolution, effectively imaging the Sun's atmosphere in 3D from the chromosphere well up into the middle corona with unprecedentedly high fidelity and high dynamic range; that is, faithfully reproducing extremely faint details of the emission in the presence of bright sources—a compatibility on par with modern cameras that employ direct imaging. By imaging over a broad frequency range with high quality and resolution, FASR captures the precise state of the solar chromosphere and corona in 3D as a coupled system on timescales as short as 10 ms.

As a solar-dedicated facility, FASR will observe the full solar disk every day. FASR's camera-like capability across a very broad frequency range, combined with its simultaneous high spectral, temporal, and angular resolution will open up many new windows to bring remarkable advances to solar and space weather sciences. Its unique measurements at long wavelengths are also highly complementary to the existing fleet of space-borne missions and ground-based facilities, as well as the other missions/facilities deemed as high priorities by the panel.

FASR consists of two interferometric array subsystems, each comprising of on the order of 100 antennas, which together cover an unprecedented two-orders-of-magnitude frequency range from 200 MHz to 20 GHz. The exact number, type, and configuration of the antennas in each array are chosen to optimize its imaging capabilities in order to address the key science objectives outlined above. The antennas will be distributed over an area with a diameter of ~4 km, providing an angular resolution of 1″ at 20 GHz. FASR exploits radio astronomy techniques that have a substantial heritage, namely, Fourier synthesis imaging. The successful operations of FASR's pathfinder, EOVSA, have demonstrated FASR's scientific potential and have retired essentially all technical risks. There are no technological impediments to building FASR.

Despite being prioritized by several previous decadal surveys, FASR has not yet received funding for construction, primarily owing to the lack of an appropriate funding vehicle in past years. With the availability of NSF's new MSRI line, such a funding vehicle now exists. It is therefore a timely imperative to implement FASR and, upon its commissioning, support its operations as a community facility.

Coronal Solar Magnetism Observatory

The dynamical evolution and reconfiguration of the magnetic field in the upper solar atmosphere are critical processes underlying the origin of the quiescent, hot solar corona, the solar wind, and extended heliosphere, as well as the impulsive release of energy in large-scale solar flares and eruptions. Proper assessments of the field strength and topology, as well as of local plasma thermodynamic parameters are necessary to derive the energy associated with these events. However, to date, there are still very few direct measurements of the coronal magnetic field to support models. The community is deeply invested in this topic, as testified by numerous complementary techniques that have emerged in recent years to estimate the coronal field (LRG, Section B.3). By providing synoptic observations of both magnetic field and plasma properties of the whole upper solar atmosphere (up to about 2 $R_\odot$), COSMO will fill this critical information gap, as already recognized in the 2013 decadal survey. With a suite of three complementary instruments, a large field of view and synoptic operations, COSMO will address many of the target science objectives of PSGs 1–3.

The high-level science objectives provided by the COSMO community input paper are

- Understand the storage and release of magnetic energy by characterizing the physical processes leading up to eruptions.
- Understand CME dynamics and consequences for shocks by characterizing local and global interactions.
- Determine the role of waves in solar atmospheric heating and solar wind acceleration by characterizing spatial and temporal wave properties.
- Understand how the coronal magnetic field relates to the solar dynamo and evolving global heliosphere by characterizing variations on solar cycle timescales.

The central instrument of COSMO is a stand-alone, 1.5 m (refractive) coronagraph with a field of view from 1.03 to 2 $R_\odot$ and a spatial resolution of 2″, the Large Coronagraph (LC). LC builds on the heritage of well-established instruments like CoMP and the newly commissioned UCoMP, employing tunable filters to obtain spectro-polarimetric observations in a variety of coronal lines in the visible and near-IR, sampling plasma up to 5 MK. The multiline capability provides the plasma density and velocity both along the line-of-sight (LOS) and in the plane of the sky (POS), while the linear polarization of the emitted lines is a measure of the POS direction of the magnetic field. This technique is mature and has proven uniquely valuable to assess the magnetic configurations leading to eruptions. The LOS strength of the field will be recovered from the Zeeman effect observed in circular polarization; while the signal is extremely low (of order of 10^{-3} of the coronal emission), the feasibility of this technique is currently being validated by first results with the coronal instruments of Inouye. The collecting area and spatial sampling of the LC ensures that the necessary measurements can be obtained on timescales of minutes. This measure will be combined with estimates of the POS field strength derived from the phase speed of Alfvén waves through coronal seismology.

The COSMO suite comprises two other instruments highly complementary to LC: a full-disk/limb imaging spectropolarimeter (ChroMag) producing photospheric and chromospheric full-disk magnetic field maps at 1-min cadence, and a white-light K-coronagraph (K-Cor) imaging the sky up to 3 $R_\odot$ with a cadence of 15 sec. A large telescope on the ground allows for high time cadence, upgradeable instruments, and, most importantly, a long period of operation (decades).

Multiple science objectives can be addressed with the COSMO suite of instruments, both on short and long (decade) timescales, including, for example, the following:

- Constrain the evolution of the global magnetic field on solar cycle timescales.
- Define how the chromospheric magnetic field shapes the global magnetic field.
- Determine the effect of magnetic fields on coronal plasma properties.
- Constrain the contribution of Alfvénic to chromospheric/coronal heating.
- Characterize acceleration and transport mechanisms in the solar wind.
- Identify which magnetic configurations determine the timing, location, and extent of free energy release.
- Quantify the magnetic energy buildup prior to an eruption and discriminate between models of CME drivers.
- Determine the mechanisms driving CME acceleration, expansion, and formation of shocks in the middle corona.
- Improve SEP forecast and warnings.

COSMO is in an advanced state of design. The K-Cor white-light coronagraph is already operational, while Chro-Mag will be deployed soon to MLSO. Supported by an NSF grant, the LC is now undergoing final design and construction cost determination along with a site survey campaign. In parallel to hardware development, the project is actively promoting development of modeling and analysis tools, including forward modeling of Stokes profiles of coronal forbidden lines, tomographic reconstruction of vector fields from polarization measurements, time-distance coronal seismology, and inversion of coronal polarization diagnostics.

COSMO will observe the whole Sun, every day, with a synoptic program and community-driven campaigns. This consistent coverage makes it highly complementary to other solar telescopes and missions, enhancing the value of other ground- and space-based HSO assets.

Next-Generation Global Observations Network Group

Long-term, continuous, ground-based, full disk observations of the Sun are essential for understanding and predicting solar activity and the space weather and climate variations that are driven by the variable Sun. Such observations have been carried out by two worldwide networks: Solar Observing Optical Network (SOON) and GONG. Together these networks provide nearly continuous observations of active regions and H-alpha emission, helioseismic measurements of solar velocities, magnetic fields, and eruptive phenomena. These observations are essential for both fundamental research and operations concerning prediction of space weather hazards. Both SOON and GONG instruments are nearing the end of their useful life (~2030), are becoming technologically obsolete, and need to be replaced and upgraded. Multiple agencies (DoD, NASA, and NSF) and their operational units and grantees are dependent on these systems for carrying out their funded missions.

The next generation of the GONG network (ngGONG) with upgraded and augmented instrumentation would centrally support multiple scientific objectives within PSGs 1–3 as well as SH EO 1, including the following:

- Helioseismology as a window into the Sun's interior and far-side
- Origin of solar and stellar magnetic fields
- Understanding and predicting solar eruptions and space weather
- Understanding magnetic "connectivity" throughout the heliosphere
- Understanding the Sun as a star, in support of fundamental astrophysics and physics of stars
- Providing physical, environmental context for high resolution and space missions

ngGONG instruments would cover both a wider range of solar phenomena than current systems, as well as observe with higher spatial resolution. The network would include spectropolarimeters for measuring magnetic fields at multiple heights; broadband imagers and coronagraphs for observing violent solar ejecta; and high-resolution and high-cadence Doppler velocity instruments for helioseismic measurements, while at the same time preserving current capabilities required for space weather operations. All of the upgrades are technologically ready for implementation.

By its global nature, ngGONG is necessarily internationally deployed and provides strong operational value. Thus, it would be beneficial to share costs between international partners as well as between domestic government agencies, such as with NOAA.

Project Readiness

Project readiness as deemed by the panel, with applicable augmentations and adjustments, is described above per mission concept and ground-based facility. All of the concepts have substantial components that are technologically ready. However, a common thread—namely, for the space-based missions—is the critical need for higher telemetry and data processing capabilities. This issue is further amplified for constellations and satellites with deep space orbits. To this end, the panel has provided a mission-enabling infrastructure consideration concerning high-data-volume missions in Section B.5.4, "Mission Enabling."

Living with a Star and Solar Terrestrial Probes Mission Line

The Solar Terrestrial Probes (STP) program addresses the following objectives:

- *STP-1:* Understand the fundamental physical processes of the complex space environment throughout the solar system, which includes the flow of energy and charged material, known as plasma, as well as a dynamic system of magnetic and electric fields.
- *STP-2:* Understand how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields.
- *STP-3:* Develop the capability to predict the extreme and dynamic conditions in space in order to maximize the safety and productivity of human and robotic explorers.

The LWS program goals relevant to SH goals, as stated in the LWS report *10-Year Vision Beyond 2015* (NASA 2015), include the following:

- *LWS-1:* Deliver the understanding and modeling required for useful prediction of the variable solar particulate and radiative environment at the Earth, Moon, Mars, and throughout the solar system.
- *LWS-2:* Develop a fuller understanding of how and to what degree variations in the Sun's radiative and particulate outputs will in conjunction with other forcing factors affect regional and global climate in the present century.

Furthermore, the LWS program supports 10 strategic science areas (SSAs; updated in 2019 from the 2015 report). The SSAs relevant to SH goals are as follows:

- *SSA-I:* Origins and Variability of Global Solar Processes
- *SSA-II:* Solar Eruptive and Transient Heliospheric Phenomena
- *SSA-III:* Acceleration and Transport of Energetic Particles in the Heliosphere
- *SSA-IV:* Variability of the Geomagnetic environment
- *SSAI-IX:* Solar Impacts on Climate
- *SSA-X:* Stellar Impacts on Planetary Habitability

The GHC, SPO, and EHC mission concepts encompass exploring both fundamental processes and understanding their impacts on society as they aim to capture a truly global view of the Sun. The science goals from these concepts are central to STP-1, STP-3, LWS-1, and LWS-2 and directly relate to SSA-I (particularly SPO) and SSA-II (particularly EHC), with supporting contributions to SSA-III, SSA-IV, SSA-IX, and SSA-X.

An Interstellar Probe would address fundamental knowledge gaps within STP-1 and STP-3, the latter being tied to the understanding of GCR and ACR propagation and modulation.

The MCEM concept applies to both the STP and LWS programs, addressing STP-1, STP-3, LWS-1, and LWS-2, as it seeks to understand fundamental physical processes related to high-energy phenomena with applications to their societal impacts through the study of underlying eruption drivers and subsequent radiation environments. The goals also directly relate to SSA-II and -III, with supporting contributions to SSA-I.

The HDTC mission concept is primarily connected to the LWS program—namely, LWS-1 and LWS-2 along with SSA-II and SSA-III—as it focuses on capturing CME measurements as they propagate through interplanetary space en route to 1 AU. The mission concept goals also support the STP program by contributing to major knowledge gaps in the understanding of ICME structure and evolution.

Interdisciplinary/System Science Approach

The mission concepts and facilities put forward by the panel all have ambitious and far-reaching science goals and objectives that naturally lend themselves to system-level science and interdisciplinary studies.

Contributions to system science include providing complete global context of the variable magnetic and radiative environments in the corona and heliosphere; connecting the global solar magnetic field with plasma and particle distributions in the solar wind; capturing the birth, flow, and dissipation of explosive events and escaped energetic particles from multiple vantage points and/or scale sizes; constraining the solar wind parameters impacting the outer heliosphere and cosmic ray populations; and characterizing the formation and boundary conditions of the entire heliosphere. The level of impact that each mission concept and facility has on these system-level contributions is summarized in Figure B-26.

PSGs 1–3 and associated missions/facilities all tie into understanding various heliospheric radiation and magnetic field environments as well as the physics of space weather, which provide critical inputs for magnetosphere and ionosphere–thermosphere–mesosphere research. These goals also map to NASA's core exploration programs, providing unique opportunities for interdisciplinary studies incorporating lunar and planetary science (EO 2). PSG 4 enables comparative studies between the heliosphere and the astrospheres of other stars in the galaxy. All of the PSGs provide an opportunity for advanced interdisciplinary studies with astrophysics through a bi-directional flow of information (EO 1). The LRG is a common thread pervading many of the SH goals and objectives.

Supporting functional team engagement between these communities (both internal and external to SH) through programs such as LWS and through cross-divisional funding is key to enabling truly system-level collaboration and interdisciplinary studies.

B.5.3 Heliophysics System Observatory

By the NASA definition, the HSO comprises the fleet of operational spacecraft observing the Sun, heliospheric space, geospace, and planetary environments to understand the solar system through a concerted effort. The current fleet operated by NASA along with international partners is extensive in its pursuit of foundational science goals but lacks key constituents relevant to SH objectives, including maintained direct observations of the solar poles from high latitudes; maintained global coverage of the Sun from multiple vantage points; high-energy imaging and spectroscopy capturing nonthermal processes during energetic events; in situ mesoscale measurements covering structural extents of propagating CMEs; and the capability to measure rapidly evolving coronal magnetic fields. The steady degradation of the Voyager spacecraft is also resulting in a conspicuous gap in the exploration of the furthest reaches of the Sun's atmosphere—although it is critical to continue the operation of New Horizons as it transits the outer heliosphere and enters the heliosheath. As New Horizons is currently managed by the Planetary Science Division, it behooves NASA to coordinate science and operations management between the Heliophysics and Planetary Science Divisions. The mission concepts put forward by the panel as priorities directly address these gaps in the HSO infrastructure from the SH perspective.

The HSO would markedly benefit from increased operational synergy within the space-based fleet, but also, critically, with ground-based facilities. Not all measurements need to be taken from above Earth's atmosphere, such as baseline photospheric magnetic field measurements, and indeed some cannot be owing to launch vehicle, spacecraft accommodation, and telemetry constraints. Equally true, Earth's atmosphere shields us from observing critical solar physical processes from the ground, including nearly all emission more energetic than the visible spectrum and interplanetary fields and composition. Making concerted use of complementary measurements between ground- and space-based instrumentation through an "expanded HSO" is necessary to reduce resources lost toward redundancy and to fill critical knowledge gaps.

There are elements currently within the HSO that have become baseline architecture, precipitating the need to maintain and/or enhance their capability. The continuous full-Sun EUV coverage by SDO since 2010 is a prime example as these observations have become fundamentally salient for tracing hot plasma flows and connectivity for a wide breadth of SH research. Continuing to maintain the capabilities of SDO (either as part of the EHC constellation or as a standalone mission), ideally with added spectral diagnostics, is an acute need for the SH communities. Another key example of continued needed capabilities are in situ measurements of the solar wind, including plasma and field diagnostics, such as those that have been provided by Wind and ACE and will be improved upon by the upcoming IMAP mission.

Combining the current state of the HSO with the priority space-based mission concepts and ground-based facilities along with the support of critical elements described by the panel would result in a tremendously robust research program for the Heliophysics Division. All of these elements combined, especially if coordinated more productively with existing ground-based facilities, would enable a solar system view of the Sun and its entire influence—from the inner workings of our stellar neighbor to its interaction with the interstellar medium and from particles accelerated at local reconnection sites to their subsequent impacts at planetary bodies.

B.5.4 New Research and Infrastructure Considerations

The SHP has identified areas in which new attention or increased resources could significantly enhance the ability to realize the SH science goals and emerging opportunities (see Table B-6 later in the chapter). The considerations presented here are based in large part on the community input papers submitted to the decadal survey. The considerations fall into four categories: Mission-Enabling; Observation and Instrumentation; Data, Theory, and Modeling; and Programmatic.

Mission Enabling

High-Data-Volume Missions

Executing much of the SHP's identified research activity requires deployment of multispacecraft and distant heliosphere missions that will generate high data volumes, placing unprecedented demand on ground receiver networks. Indeed, telemetry allocations for current and upcoming missions are already taxing the Deep Space Network. It is imperative that a major expansion of the Deep Space Network capacity and development of optical communication technology will be required to match the coming demand. Concurrently, investments are needed in improving smart onboard processing capabilities.

In addition to the telemetry concerns, the processing demands of these anticipated high-volume data sets could easily stretch beyond the capacity of any single mission. In order to make full use of the investment in these data sets, a new funding paradigm that removes some of the burden from the mission teams and increases the reach of funded analysis opportunities would significantly optimize data usage.

Access to Space

NASA's Heliophysics Low Cost Access to Space (H-LCAS), Flight Opportunities in Research and Technology (H-FORT), and Technology and Instrument Development for Science (H-TIDeS) programs have been demonstrably successful at enabling and maturing key flight technologies that would otherwise be untestable. These programs support laboratory-based technology development as well as environmental testing through sounding rockets, high-altitude balloons, and CubeSats. Commercial opportunities have also recently become available with complementary capabilities, adding available resources to a highly subscribed infrastructure. These programs uniquely accept high-risk, high-reward projects and, in turn, improve the return on investment from Explorer- to flagship-size missions that rely

TABLE B-6 Sun and Heliosphere Goals, Objectives, and Opportunities

Goals	Objectives
PSG 1: How does the Sun maintain its magnetic activity globally from *pole to pole*?	a. Determine the role of the polar and high latitude magnetic fields and flows in the evolution of the solar dynamo. b. Determine how the dynamo-generated fields emerge through the surface and shape the 3D structure of the solar atmosphere and heliosphere. c. Determine the nature of global flows and inertial waves at all latitudes, down to tachocline depth, and their relationship to the solar dynamo. d. Determine how solar magnetism changes over the solar cycle, from the solar interior through the highly coupled solar atmosphere.
PSG 2: How do the Sun's magnetic fields and radiation environments *connect* throughout the heliosphere?	a. Demonstrate how photospheric and chromospheric dynamics drive the corona. b. Determine the role quasi-steady processes play in the heating of the solar corona and the acceleration of the solar wind and suprathermal particles. c. Understand how the magnetic field of the corona and inner heliosphere is structured, how it evolves, and how it connects to and influences the interplanetary magnetic field on varying timescales. d. Trace the origin of solar wind variability, and identify the extent to which it is owing to local kinetic processes or underlying global solar activity.
PSG 3: How do solar explosions *unleash* their energy throughout the heliosphere?	a. Determine how and where magnetic energy is stored and suddenly released, from kinetic to global scales, to drive solar transient events. b. Understand the dominant fundamental energy conversion and transportation mechanisms that energize plasma and particles throughout the heliosphere. c. Measure and track the rapidly evolving properties of solar eruptions from the solar surface through interplanetary space. d. Improve methods for forecasting and nowcasting of solar eruptions at the Sun and for predicting the subsequent impacts on interplanetary radiation environments.
PSG 4: How is our *home in the galaxy* sustained by the Sun and its interaction with the local interstellar medium?	a. Ascertain the physical processes from the Sun to the LISM that shape the heliosphere and determine the spatial and temporal dependence of its boundaries. b. Establish how the dynamics and evolution of the global heliosphere are affected by solar activity, and by the LISM and its inhomogeneities. c. Determine how pickup ions are heated and accelerated across the termination shock, evolve in the heliosheath, and escape across the heliopause into the LISM. d. Infer how and where anomalous cosmic rays are accelerated, and how they and galactic cosmic rays are modulated by the Sun, heliosphere, and LISM.
Longer-range goal	Revolutionize our understanding of dynamic solar processes through rapid, direct observational measurements of magnetic fields throughout the solar atmosphere and inner heliosphere.
Emerging opportunities	Enable opportunities for multidisciplinary research to holistically explore how solar and stellar activity and the interactions of stars with their interstellar environments impact planetary systems. Leverage upcoming opportunities through the lunar, Mars, and planetary exploration programs to enable cross-cutting solar and heliospheric research from emerging platforms and unique environments.

NOTE: Acronyms defined in Appendix H.

on mature technologies to buy down risk. The panel recognizes the immense value of these programs, not only to mature technology but also to develop a diverse workforce and encourages elevated support in the coming decade.

Multipoint Mission Capability

Multispacecraft missions are becoming an increasingly necessary component of the HSO to tackle progressively complex and targeted science objectives. Indeed, a significant fraction of the SH community input papers submitted called for multipoint or constellation missions. Exploring low-cost platforms that can support heliophysics payloads is therefore a pertinent investment. Solar sails, for example, are a potential multispacecraft enabling technology, and demonstrations of their use and other relevant technologies for heliophysics applications would be of considerable benefit in the long-term vision of multipoint observation feasibility.

Observation and Instrumentation

Middle Corona Observations and Instrumentation Development

High-resolution spectroscopic emission-line measurements in the middle corona (~1.2–6 $R_\odot$), building on the successes of SOHO Ultraviolet Coronagraphy Spectrometer, are required to further the understanding of formation, heating and acceleration of the solar wind, initiation and release of CMEs, and formation of CME shocks. Spectroscopy of coronal hydrogen and heavy ions provides direct measurements of particle distributions from which density, nonthermal heating, and outflow speeds can be traced as a function of altitude. Currently, there is an observational gap in this range (see Figure B-8), because no currently flying missions host instrumentation able to make high-resolution spectroscopic measurements. Advancing the technological readiness of next-generation instrumentation targeting the middle corona is of strategic importance and requires investment at the instrument development stage, through programs such as H-TIDeS and H-FORT (or their equivalent) to prepare for deployment on future missions.

High-Energy Observations

Solar flare accelerated particles compose a huge fraction of the flare energy budget. They influence how eruptive events develop, are an important source of high-energy particles found in the heliosphere, and are the single-most important corollary to other areas of high-energy astrophysics. RHESSI transformed the knowledge of the properties of high-energy particles in solar eruptions. It also revealed new gaps in the understanding of energy transport within the solar atmosphere and the heliosphere (e.g., coronal sources of accelerated particles above flare loops, quasi-periodic pulsations in HXR signatures, and the displacement between HXR and gamma-ray sources).

The high-energy solar physics community exploded during the operational years of RHESSI. However, there is no currently operational or planned U.S. mission to study the high-energy Sun and continue with this momentum. Focusing HXR optics technology and gamma-ray detectors have been developed over the past decade and are ready to be leveraged. Concurrently, rapid development has occurred in spectroscopic imaging at high thermal energies, which is crucial for constraining active region and flare heating sources. It is important to take advantage of the past decade of high-energy technology development as well as the expertise from generations of solar physicists trained to interpret high-energy spectra before these capabilities are lost.

Heliospheric Mesoscale Observations

There is a need for the development of heliophysics missions capable of studying space plasmas on intermediate "mesoscales," which connect microphysical kinetic processes to large-scale solar wind structures. The current HSO concept for monitoring the Sun and inner heliosphere is very much focused on large-scale structures and processes, while past and near future constellation missions such as MMS and HelioSwarm are focused on small-scale kinetic physics, leaving a large gap in between the two that needs to be filled. For example, HSO observations can reveal the large-scale characteristics of shocks, and small constellations (and individual spacecraft) might be able to study very local particle acceleration at that shock, but currently nonexistent mesoscale observations are needed to observe how localized deformations in shock shape affect particle production and transport by that shock as a whole. More broadly, mesoscale observations could allow us to understand how large-scale solar wind variability cascades down to smaller scale sizes, thereby affecting microphysical processes that are important for understanding and predicting solar wind behavior.

Support for Inouye Solar Telescope and Other Ground-Based Observatories

The 4 m, visible-IR Inouye observatory is the largest solar facility supported by NSF. Still in its commissioning phase, Inouye is starting to produce scientific results that point to its potential to accelerate the understanding of many crucial physical processes operating at the Sun and the heliosphere. Of great interest for the LRG as identified by the panel, the first detection of the elusive coronal Stokes V signal in an active region has just been reported, holding promise of consistent measurements of the coronal magnetic field.

It is essential that NSF provides continuous support for Inouye scientific operations to fully achieve the scientific potential of this major investment. This support includes maintenance and upgrading of critical components (e.g., high-speed cameras, integral field units, and state-of-the-art adaptive optics systems like multiconjugate adaptive optics and limb-adaptive optics), as well as second-generation instruments addressing pressing scientific questions. Of equal importance is increased support for data analysis and development of advanced techniques, necessary to maximize the science yield from the very large volume of data obtained. In addition, smaller, university-led instruments and facilities contributing to ground-based observatories provide critical infrastructure, both scientifically and academically. The panel strongly encourages continuing support for these programs.

Data, Theory, and Modeling

Data and Modeling Standards and Integration

Characterizing the SH system requires a wide variety of data (e.g., remote sensing, in situ detectors, imagers, and spectrographs) and theoretical models (e.g., atomic physics models and MHD and radiative transfer models) that are highly heterogeneous in their applicability and approximations, cadence, resolution, and time coverage, and diagnostic capabilities.

Currently, many complex data sets require intensive processing before physical parameters can be derived and analyzed, and often these data products are not optimized for integration with physical models. The sheer data volumes involved, both from observations and models, also make local analysis less and less feasible. The required resources or expertise acts as an obstacle to accessibility and results in a fragmented research community.

During the past decade, there has been progress by the HSO through integrated data delivery services (such as the Virtual Solar Observatory [VSO]) and a common platform for running community provided models in NASA's Community Coordinated Modeling Center (CCMC). However, the burden of model and data assimilation still largely relies on each individual researcher and/or research group. At a minimum, guaranteed support for missions and facilities would increase production of "science-ready" data products and lower the barrier of entry for new users and facilitate scientific use of the data. Another useful investment focus would be research on how to better combine heterogeneous data to obtain physical results that cannot be produced by single observations.

On a larger scale, the panel considered the benefits of an agency-funded center devoted to the creation of standards for the integration and homogenization of data and models. This center could be an extension of the CCMC, could also be part of the National Solar Observatory (building on the success and expertise of the VSO) or, even better, could integrate both. Such a center could have a tremendous impact in enabling multidisciplinary research, akin to the impact of the University Corporation for Atmospheric Research (UCAR) with the development of the Network Common Data Form (NetCDF) format and would significantly lessen the burden that is currently placed on individual researchers for data processing and integration.

The overarching mandates of this center would ideally include:

- Development of a central database by unifying data from current major databases that would allow the ongoing contribution of atomic results and modeling codes from the community.
- Utilization of novel formats for data distribution and analysis like Zarr[3] to help the heliophysics community take advantage of cloud computing and noncentralized data repositories, as well as designing strategies for the modernization of existing repositories. This implementation includes investigating novel data formats better suited to multidimensional data and cloud-based computing.
- Design the architecture for data distribution in upcoming missions and how to integrate existing missions within such architecture. This architecture can leverage expertise within and without heliophysics, such as data architecture developed by Inouye, Vera C. Rubin's Large Synoptic Survey Telescope (LSST), PanGEO, and so on.

[3] Zarr is an open-source data format designed to store and manage large multi-dimensional arrays in a chunked, compressed manner (Zarr.dev 2025).

- Design and oversee machine learning applications that take advantage of this infrastructure to enable better data compression, fill gaps on data, modernize historical data, unify atomic physics data sets and models, and so on.
- Provide guidelines for the ethical use of artificial intelligence in heliophysics.

Modernization of Theory and Modeling Support and Infrastructure

Theory and modeling are vitally important to the continued success of heliophysics research. They form a critical understanding from fundamental principles that motivate new areas of science, and contribute to interpretation and prediction of observations, which are becoming increasingly detailed with modern instrumentation. Theory and modeling also play a key role in the development of new ways to visualize the data and can improve the design of new instruments while enhancing the overall scientific return of space missions. A key consideration from this panel is that theory and modeling continue to be supported.

The past decade has seen greatly increased computational capacity, with cloud resources, storage and analysis, and artificial intelligence. Numerical modeling in heliophysics has advanced to the level where it can take advantage of these and other new opportunities to tackle new challenges, including advancing comprehensive data-driven models and real-time prediction of solar events. At the same time, the cost of the hardware, software, and person power needed to harness these new and emerging technologies has become as expensive as space missions.

To take full advantage of the heterogeneity of modern computational architecture in developing complex models in heliospheric physics requires an expert workforce with overlapping expertise. Specifically, computational physicists with software engineering skills and software engineers with knowledge of the heliospheric science will be required. Heliophysics problems require multiscale, multiphysics plasma models with vast dynamic ranges in time and space, data-model fusion, and a continuously improving theoretical toolkit. Further challenges in the next decade include improving model-fidelity through a higher level of error analysis, uncertainty quantification, and data assimilation. Ensemble modeling and multimodel ensemble modeling will be the essential components to reach such a high level. New methods of data assimilation specific to heliophysics need to be developed, because traditional data assimilation may not always be applicable.

Existing NASA programs such as HSR, HTMS, LWS-FST, LWS Strategic Capabilities, and NASA DRIVE Science Centers, as well as NSF programs such as SWQU, ANSWERS, SHINE, STC, are important foundations and merit continuation. However, these programs cannot fully answer the computing challenges that the new decade poses. Specific problems in SH physics would be ripe for breakthroughs if only the advantage of the existing and nascent computing power is utilized.

Additionally, heliospheric models are meant to serve the community rather than just the developers. For the next decade, the large teams with overlapping expertise mentioned above are necessary to achieve this, alongside a flagship community science models program. Such a task force might consider (1) benchmarking other NASA divisions (e.g., Earth Sciences), other agencies (NSF, DOE), and international organizations for community models; (2) defining the scope of the program; and (3) outlining a possible implementation of a program for the U.S. heliophysics community.

Maintain a Robust Outer Heliosphere Research Program

Continued support for outer heliosphere research is important for understanding our home in the galaxy. Large-scale computer modeling, for example, is one of the primary ways in which a global picture of the heliosphere and its critical boundaries is obtained. Such models must include realistic boundary conditions in order to understand how solar disturbances propagate throughout the heliosphere. The models must be constrained by spacecraft observations, particularly in the location of boundaries and the nature of plasma flows and fields.

Other important research areas include (1) the properties and propagation of dust in the heliosphere, which provides important, and perhaps under-appreciated, information about the history of the heliosphere; (2) the interaction of cosmic rays with the heliosphere—such as ACRs, GCRs, and TeV-energy CRs, which are deflected by, and create gamma rays with, their impact with the Sun—and their solar cycle dependence; (3) kinetic modeling of the heating and evolution of PUIs in the heliosheath, and the evolution of disturbances in the LISM. This research program will enhance the scientific return of the Voyager missions, and the upcoming IMAP mission, and are of critical importance for interpreting observations of a future interstellar probe mission.

Moreover, this research involves fundamental multicomponent plasma physics processes that occur throughout the heliosphere, such as particle acceleration and heating, magnetic reconnection, turbulence, and instabilities. This science is also at the boundary of both astrophysics and heliophysics, providing an excellent opportunity of cross-disciplinary collaboration.

Programmatic Considerations

Expansion of Explorer Program to Include a High-Cap Mission Line

It would be valuable to extend the Heliophysics Explorer mission class to include a principal investigator (PI)-managed mission line with a $600 million to $1 billion (fiscal year [FY] 2023) cost cap that would fill the capacity gap between Medium-Class Explorers (MIDEX) ($300 million, FY 2023) and flagship (>$1 billion). The ambitious SH science goals for the coming decade exacerbate an existing gap between the measurement requirements needed for tackling present science questions and the resources available to mission opportunities to adequately address them. This new mission line would be analogous with the highly successful Discovery Mission Program, to which the planetary science decadal survey (NASEM 2023) recommended an increase of cost cap to $800 million in FY 2025, and the new PI-led Astrophysics Probe Explorer (APEX) mission line, with cost cap up to their flagship mission bound of ~$1 billion. It would be advisable for science objectives to remain generally open, but within the scope of the LWS and STP directed science lines.

Timeliness of Proposal Awards

A worrying trend of routinely delayed proposal awards is becoming increasingly problematic for the community. Delayed awards often lead to wasted use of resources from unnecessary development of additional proposals while awaiting the delayed results. Even more concerning, however, is the impact that these delays have on students, postdocs, and early-career professionals whose education and career trajectories can be irrevocably affected by awards announced off-cycle (e.g., after the start of the academic year). It is critical that proposal calls not overlap with related open calls and that award cycles take into account key decision point timelines for the target community.

Streamline NASA Heliophysics Mission Development Oversight Requirements

It is important for the NASA Heliophysics Division to consider a review of mission development management practices to find ways to streamline these procedures and reduce burden on the mission teams. Heliophysics missions have seen a marked increase in costs over the past decade that greatly outstrip inflation. This escalation can be attributed to multiple factors, but a major contributor is a steady increase in the level of oversight and the number of reporting requirements levied on the spacecraft and instrument teams, with no perceived concomitant improvement in mission reliability. It will become increasingly difficult to execute SH science goals if mission oversight costs are not reigned in.

Support for Laboratory Plasma and Atomic Physics

Similar to the justification for cross-disciplinary studies covered in EO 1, support for laboratory astrophysics will enable further scientific advancement because it provides unique environments in which to observe plasma phenomena and disentangle spatio-temporal characteristics of plasmas. In a controlled laboratory setting, plasma behavior can be probed at a level of detail that is not possible in space. This field of research provides unmatched opportunities to measure and quantify the interactions between macroscale physics and microscale dynamics in three dimensions, such as in the case of probing reconnection, shocks, and turbulence in a laboratory setting. The knowledge gained from these experiments will be invaluable to deciphering multispacecraft observations of the associated heliospheric phenomena and inform 3D models and simulations. Success in this field will require dedicated funding over the long term, as well as educational experiences and tools to train new generations of students to design and run experiments.

Much of the ability to study energization and acceleration of plasma depends on the understanding of atomic physics. Currently, much of the models and interpretation of solar spectra and solar wind charge states rely on availability and accuracy of atomic and molecular data. Expanding atomic databases to include physics that depart from the standard assumptions will be critical to capturing nonthermal and nonequilibrium physics both in heliophysics and astrophysics. Lastly, it is critical to quantify the limitations of atomic and molecular data, because the uncertainties in these quantities propagate into their research applications and subsequent interpretation. These improved atomic and molecular data can be validated in laboratory and observational astrophysics.

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Report of the Panel on the Physics of Magnetospheres

The magnetosphere, the region of space where the magnetic field is dominated by the contribution from a planet's internally generated field, is filled with charged particles of energies ranging from less than an electron volt (eV) to hundreds of megaelectron volts (MeV) that are transported and accelerated by magnetic and electric fields. Figure C-1 illustrates the main regions of the magnetosphere. Magnetospheres are dynamic systems owing to the interaction with the solar wind and interplanetary magnetic field (IMF), and the connections to the atmosphere and ionosphere close to the planetary surface as well as the influence of planetary satellites. All planets and moons with intrinsic magnetic fields have magnetospheres, but the most familiar and most studied example is Earth's magnetosphere.

Magnetospheric physics is the study of this interconnected system. The science involves understanding how different particle populations enter the magnetosphere and how they are heated, accelerated, and transported within the magnetosphere, either flowing through the magnetosphere or becoming trapped. It involves understanding both how the steady-state configuration of the magnetosphere is formed and maintained and the dynamic changes that occur. Strong, sustained southward interplanetary magnetic fields drive geomagnetic storms, which result in intense currents both around Earth (the ring current), along the magnetic field lines, and through the ionosphere, causing magnetic disturbances on the ground. Geomagnetic storms can also increase the radiation belt flux that can damage spacecraft and can affect the ionosphere, disrupting global positioning system (GPS) navigation. Studies of magnetospheric dynamics will lead to better understanding and predictions of the impacts of solar and solar wind variability on Earth, life, and society.

Planetary magnetospheres—especially that of Earth—are also accessible laboratories for studying the fundamental physics of collisionless plasmas, including the above-mentioned reconnection, collisionless shocks, turbulence, electromagnetic wave generation, wave–particle interactions (WPIs) and charged particle acceleration. These processes drive the dynamics observed at Earth and other planets, as well as throughout the heliosphere—at the sun, in solar energetic particle events, in coronal mass ejections, at interstellar shocks, and at heliospheric boundaries. In addition, these plasma processes occur throughout the universe, for example in supernova remnants, accretion disks, and astrophysical jets. Earth's magnetosphere is the most accessible location to study these processes in situ to better understand systems throughout the universe.

Through decades of analysis, researchers have developed a detailed understanding of the global magnetospheric configuration and its response to the solar wind. But the magnetosphere is a large dynamic system, and the wide range of temporal and spatial scales that are important have made it a challenge to disentangle many of

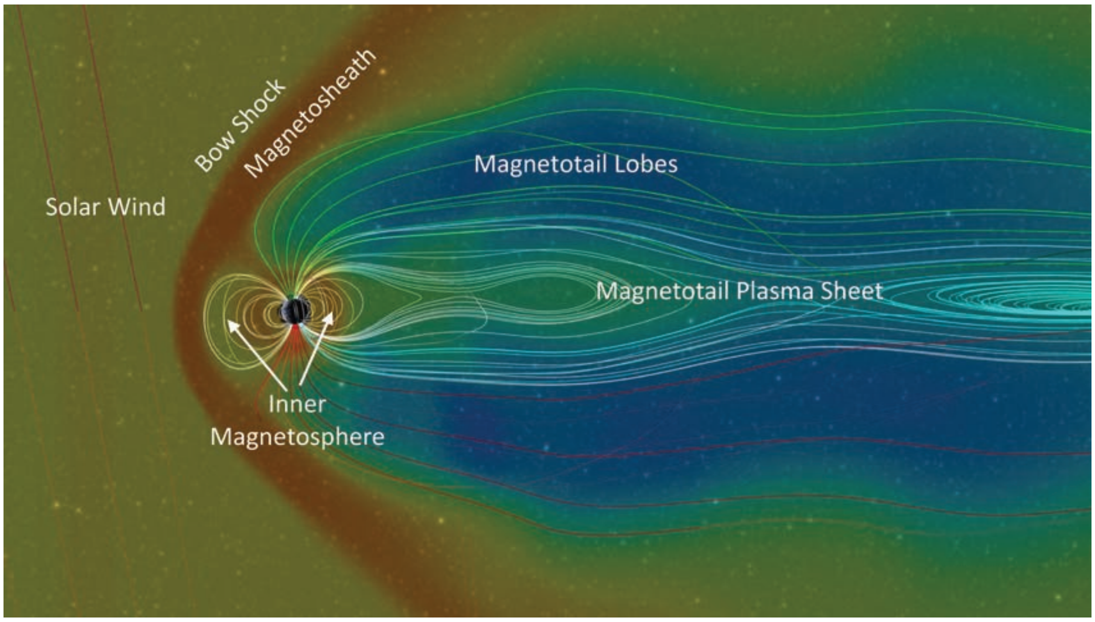

FIGURE C-1 Snapshot of Earth's magnetosphere in the x-z plane taken from a BATS-R-US simulation of the response of the magnetosphere to a coronal mass ejection (CME).
NOTES: The color indicates the density. A magnetic reconnection line can be observed forming in the near-Earth plasma sheet.
SOURCE: NASA's Scientific Visualization Studio, the Space Weather Research Center (SWRC), the Community-Coordinated Modeling Center (CCMC), and the Space Weather Modeling Framework (SWMF).

the physical processes. Missions with a few spacecraft have led to tremendous breakthroughs in the understanding of the physics at a particular scale. However, they have also revealed that understanding the full dynamics requires a multiscale perspective and requires better understanding of the linkages between the different regions of the magnetosphere. Other planetary magnetospheres have not been studied with nearly the depth of Earth's magnetosphere thus many basic questions still remain.

Section C.1 reviews the progress that has been made in the past decade. Section C.2 outlines the priority science goals (PSGs) for the next decade and show how these goals emerged from the current research activity. Section C.3 outlines a longer-range goal. In Section C.4, some emerging capabilities and technologies are identified that can be leveraged to advance the field. Last, Section C.5 outlines a research strategy for addressing the PSGs.

C.1 CURRENT STATE OF THE FIELD

Two major strategic missions—Van Allen Probes (2012–2019) and the Magnetospheric Multiscale (MMS) mission (2015–present)—launched and completed their prime missions during the previous decade. These two missions—combined with measurements from other spacecraft in the National Aeronautics and Space Administration's (NASA's) Heliophysics System Observatory (HSO), CubeSats, rockets, balloons, international missions, and ground-based assets—have led to substantial breakthroughs in the understanding of the inner magnetosphere, the physics of magnetic reconnection and other fundamental processes, global magnetospheric responses to magnetosphere–solar wind coupling and magnetosphere–ionosphere coupling. In addition, measurements at Jupiter, Saturn, Mercury, Mars and Venus have all contributed to the understanding of magnetospheric processes in diverse planetary environments. The following sections review the progress in each of these areas.

C.1.1 Inner Magnetosphere

The inner magnetosphere includes different interrelated, overlapping particle populations: the radiation belts at the highest (MeV and above) energies, the hot ring current and warm plasma cloak at lower (few eV to hundreds

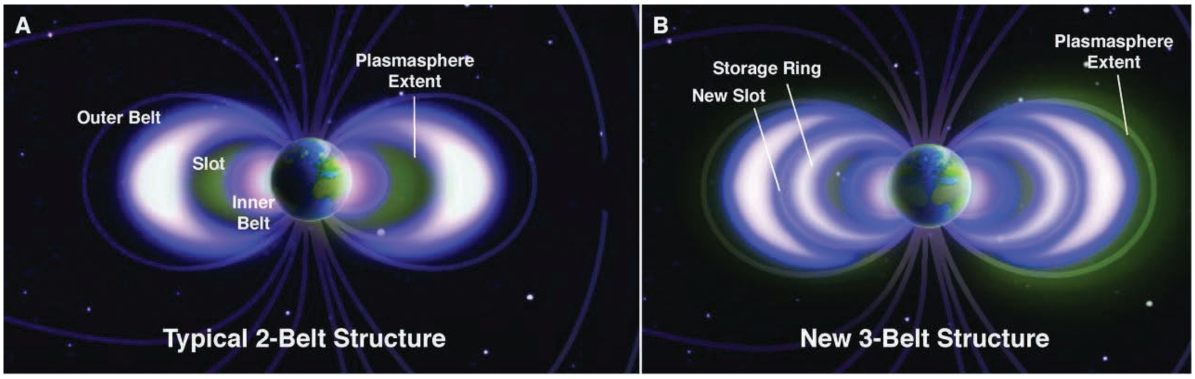

FIGURE C-2 Comparison of the typical configuration of the radiation belts, a 2-belt structure, with the transient 3-belt structure discovered using Van Allen Probes.
SOURCE: From D.N. Baker, S.G. Kanekal, V.C. Hoxie, M.G. Henderson, X. Li, H.E. Spence, S.R. Elkington, et al., 2013, "A Long-Lived Relativistic Electron Storage Ring Embedded in Earth's Outer Van Allen Belt," *Science* 340:186–190, https://doi.org/10.1126/science.1233518. Reprinted with permission from AAAS.

of keV) energies, and the cold plasmasphere at the lowest (<1 eV) energies. Progress has been made in understanding the formation, acceleration, and loss mechanisms for all these particle populations.

Understanding the dynamics of the radiation belts was a key goal of the Van Allen Probes mission because of the severe space weather impacts this energetic population can have on operating spacecraft. Van Allen Probes showed definitively that local acceleration by wave particle interactions is occurring in the center of the radiation belts, causing fast local changes in the belts. In some cases, both WPIs and the long-studied radial diffusion are needed to explain the observed energization. Other key findings on the radiation belts include the following:

- *Large-scale changes in the radiation belts:* Observations showed dramatic spatial and temporal variability, including rapid flux enhancements in the outer radiation belt. These observations revealed that large-scale, highly coherent, transient structures can form, such as a third belt, as shown in Figure C-2.
- *Radiation belt loss processes:* Orders-of-magnitude depletions of the radiation belts were observed to occur in a few hours or less, revealing complex loss processes. Van Allen Probes combined with data from CubeSats and balloons, and models, determined that these are owing to a combination of magnetopause shadowing and precipitation into the atmosphere owing to interactions with plasma waves. These results revealed the importance of studying other mechanisms such as nonlinear WPIs, drift-orbit bifurcations, and field-line-curvature scattering.
- *Importance of waves in the inner magnetosphere:* Complete orbital coverage and advanced instrumentation enabled mapping of the spatial distribution of wave types (e.g., chorus, hiss, and electromagnetic ion cyclotron) and their parameterization with magnetospheric and interplanetary activity levels. This allowed significant improvements to diffusion-based models. Data assimilation methods were developed for 2D diffusion models.
- *Moving toward radiation belt prediction:* Novel methods such as observing system experiments (OSEs) and observing system simulation experiments (OSSEs) were recently applied to improve model accuracy, elucidate the belt response to an injection or to a change in the interplanetary driver, and help with future mission planning by optimizing ranges of orbital and sensor parameters. Some radiation-belt models, along with other magnetospheric models, are candidates for the research-to-operations (R2O) pipeline.

For the lower-energy populations there have been significant advancements in understanding how the ionospheric plasma feeds the storm-time ring current. Figure C-3 shows the main transport paths. Both observations and simulations have shown that the near-Earth plasma sheet changes from a solar wind plasma dominated population to an ionospheric plasma dominated population just before or during the storm main phase, and enhanced

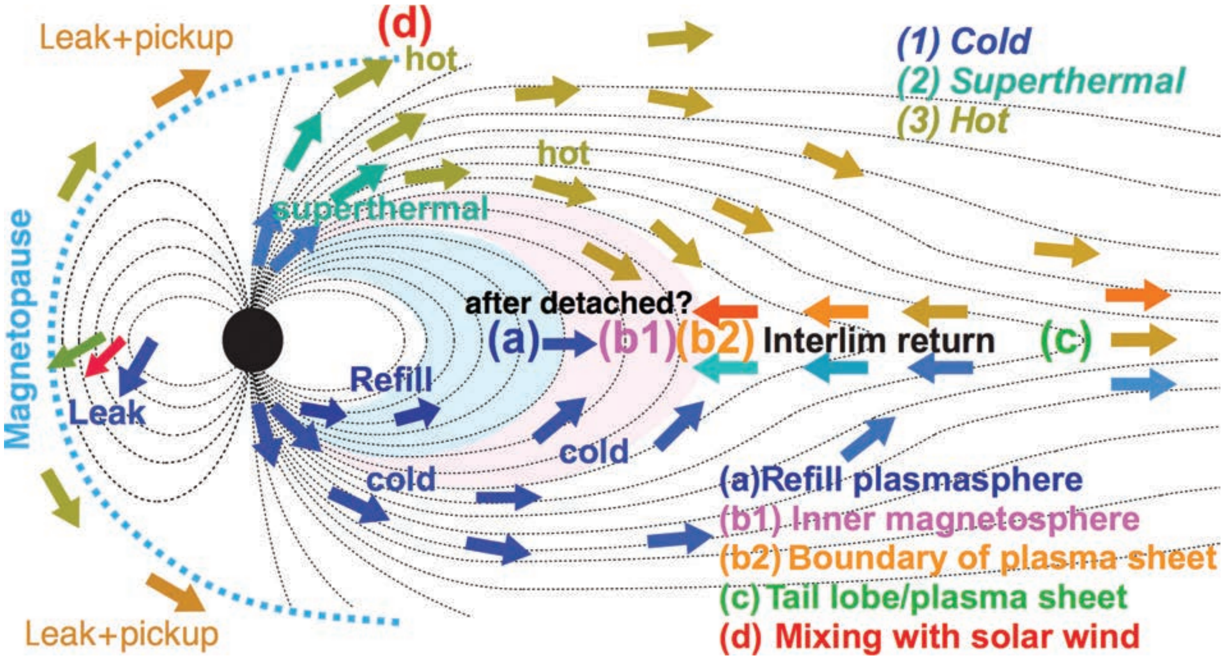

FIGURE C-3 Schematic representation of the circulation of outflowing ions in the magnetosphere and their destination.
SOURCE: Yamauchi (2019), https://doi.org/10.5194/angeo-37-1197-2019. CC BY 4.0.

convection then brings that population into the ring current. In addition, Van Allen Probes measurements showed that mesoscale energetic particle injections associated with magnetic field dipolarizations can also increase the ring current pressure and are also associated with direct outflow of O+ into the inner magnetosphere. This outflow has only a small impact on the ring current pressure owing to its low energy but is likely a source for the warm plasma cloak and perhaps the oxygen torus, a population of warm (<50 eV) oxygen ions located outside the plasmapause. Other key findings include:

- *Contributions of ion outflow sources:* There is strong auroral outflow in both the dayside cusp and the nightside auroral region during the storm main phase. The nightside auroral outflow is transported to the inner magnetosphere but does not reach high enough energies to affect the energy density. The outflow location of the energetic O+ that populates the ring current is more likely to be the cusp region.
- *Minor ions provide diagnostics of outflow mechanisms:* Data from the Arase satellite revealed that molecular ions (O_2^+, NO^+, N_2^+) with energies above ~12 keV are frequently observed in the inner magnetosphere during storm times. The high occurrence rate of molecular ions indicates that fast ion outflows from deep in the ionosphere (<300 km) occur more frequently than expected during storm times.
- *The ring current of Saturn:* The Grand Finale of the Cassini mission at Saturn explored that planet's ring current and found it to be influenced by multiple drivers, both external (i.e., the solar wind) and internal (i.e., planetary period oscillations), which trigger magnetospheric storms that result in a partial ring current of hot plasma on the nightside.

At the lowest energies, observations of plasmaspheric material at geosynchronous orbit have shown that the outward convection of this material can persist for weeks, making it a significant loss process for this population. Recent modeling suggests that high-speed outflows on convecting field lines may continue to feed the plume, which could explain its long duration. In addition, charge exchange reactions between energetic ring current ions and the ambient neutral exosphere are efficient enough to provide an additional source for the plasmaspheric plasma.

While this source is not large enough to compensate for the large losses observed, it could lead to a shortened early-phase plasmaspheric refilling period. Additional findings include:

- *Measurements of cold electron density:* While the core plasmaspheric particles most often could not be measured with Van Allen Probes owing to the spacecraft potential, the density could be determined using measurements of the spacecraft floating potential and the upper hybrid frequency. The large database of density measurements has led to new empirical models of the plasmasphere that are needed for use with radiation belt models.
- *Atmospheric loss beyond Earth:* New results from Venus and Mars have resulted in estimates of atmospheric loss that are of similar magnitude to that of Earth, despite the total lack and limited protection afforded these atmospheres by these worlds' respective planetary magnetic fields. This has raised new questions about the validity of the understanding that planetary magnetic fields protect atmospheres from ablation by the solar wind.

C.1.2 Reconnection/Turbulence/Shock

The MMS mission provided the magnetospheric community with unprecedented high time resolution, small spatial-scale observations of reconnection regions in the magnetosphere, both on the dayside and in the magnetotail. As shown in Figure C-4, for the first time, observations directly captured the electron diffusion region (EDR) of magnetic reconnection, where magnetic field lines can break and reform, explosively releasing magnetic energy into bulk flows, heating, and the acceleration of particles, and ultimately allowing solar wind energy to enter the magnetosphere and driving space weather events. MMS discoveries of reconnection include observations of nongyrotropic electron distributions, illustrating acceleration and demagnetization occurring in the region; determination that the reconnection electric field is produced by electron inertia effects at the x-line and by the divergence of the electron pressure tensor at the stagnation point; and relation of the dimensions of the EDR to the gyro-scale of trapped electrons.

Other key findings on fundamental physical processes include the following:

- *Collisionless dissipation in multiple environments:* For the first time, the dissipation in low-collisionality plasmas was directly measured in different regimes, through new measurements of energy exchange, or by measuring different terms of the collisionless Ohm's Law.

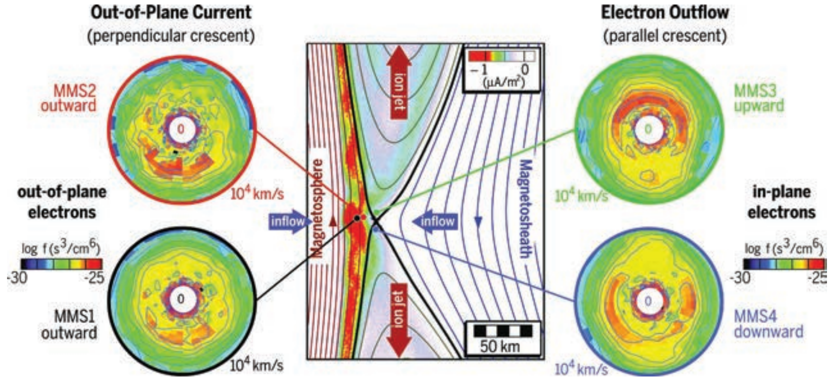

FIGURE C-4 Magnetospheric Multiscale (MMS) Mission captured the electron diffusion of magnetic reconnection at Earth's dayside magnetopause.
SOURCE: From J.L. Burch, R.B. Torbert, T.D. Phan, L.-J. Chen, T.E. Moore, R.E. Ergun, D.J. Eastwood, et al., 2016, "Electron-Scale Measurements of Magnetic Reconnection in Space," *Science* 352:aaf2939, https://doi.org/10.1126/science.aaf2939. Reprinted with permission from AAAS.

- *Interplay of reconnection, turbulence, and shocks:* Numerous MMS observations have quantified how the quasi-parallel bow shock generates turbulence, which can generate large numbers of current sheets, many of which are reconnecting. Turbulence generated during the reconnection process occurs throughout the reconnection site, and can strongly accelerate electrons, especially in the magnetotail,
- *Wide range of large-scale reconnection behaviors:* At the mesoscale and global scale, fortuitous conjunctions of missions such as the Time History of Events and Macroscale Interactions during Substorms (THEMIS) and Cluster have provided measurements along the dayside magnetopause demonstrating that reconnection can be widespread, extending over many Earth radii, or limited in spatial extent, potentially active over less than a single Earth radii in one or a series of co-existing patches. Simulation models (two-fluid, particle-in-cell [PIC], and Hybrid Vlasov) have seen similar behavior.
- *Impacts of cold plasma and heavy ions:* Observations from THEMIS, MMS, and Cluster showed that magnetopause reconnection is affected by cold plasma and heavy ions mass loading the dayside reconnection region. Plasmaspheric plumes transported to the magnetopause as well O+ both from the dayside high-latitude ionosphere and from the warm plasma cloak can reduce the reconnection rate.
- *Direct measurement of microscale turbulent cascade:* For the first time, energy cascade rates at sub-magnetohydrodynamic (MHD) scales could be measured directly in the turbulent magnetosheath and compared with global-scale cascade rates. The microscale cascade rate was found to be somewhat lower than the global rate, consistent with some theories. Notably, the cascade rate in the magnetosheath is about 1,000 times larger than in the pristine solar wind.
- *Fundamental processes beyond Earth:* Turbulence has been discovered in the magnetosheath at Jupiter, magnetosphere of Saturn, and near the Venusian bow shock. New observations have advanced understanding of the drivers, variability, and characteristics of the bow shocks at Mercury, Venus, and Mars, Jupiter, and Saturn. In particular, in the latter case of bow shocks, these other planets give access to a range of shock regimes inaccessible at Earth and the solar wind.

C.1.3 Global Magnetospheric Dynamics

Major progress has been made defining the large-scale dynamics of Earth's global magnetosphere resulting from the coupling with the solar wind, as well as the dynamics of other planetary magnetospheres.

Significant achievements and landmark discoveries over the past decade include:

- *Quantifying dynamics of kinetic shock structures:* THEMIS multipoint measurements provided the first observations of a now commonly seen structure called a foreshock bubble. These large structures accelerate charged particles locally and flow downstream where they collide with the magnetosphere, depositing energy into the system.
- *Kelvin-Helmholtz energy conversion:* Long-term studies using THEMIS data revealed that dynamic nonlinear Kelvin-Helmholtz waves occur at Earth's magnetopause boundary much more frequently (as much as 20 percent of the time) than originally thought. Building on this discovery, the community made novel measurements identifying the long-ranging effects of these twisted magnetic structures—for example, releasing energetic particle injections and seeding ultra-low frequency waves that echo throughout the magnetosphere.
- *Magnetotail transport and dynamics:* A growing number of multisatellite studies leveraging serendipitous arrangements of magnetospheric assets (e.g., THEMIS, Van Allen Probes, MMS, Arase, Geostationary Operational Environmental Satellites [GOES], and Los Alamos National Laboratory [LANL] satellites) along with ground assets (e.g., riometers, all-sky-imagers, magnetometers) in the past decade have begun to constrain the azimuthal-scale size of energetic particle injections, as illustrated in Figure C-5. Injections, sudden increases in energetic particle fluxes close to geosynchronous orbit, are associated with the range of phenomena (e.g., bursty bulk flows, dipolarizing flux bundles, dipolarization fronts) that accompany the reconfiguration of the tail following reconnection, and so help to identify the spatial scales of global magnetotail dynamics.

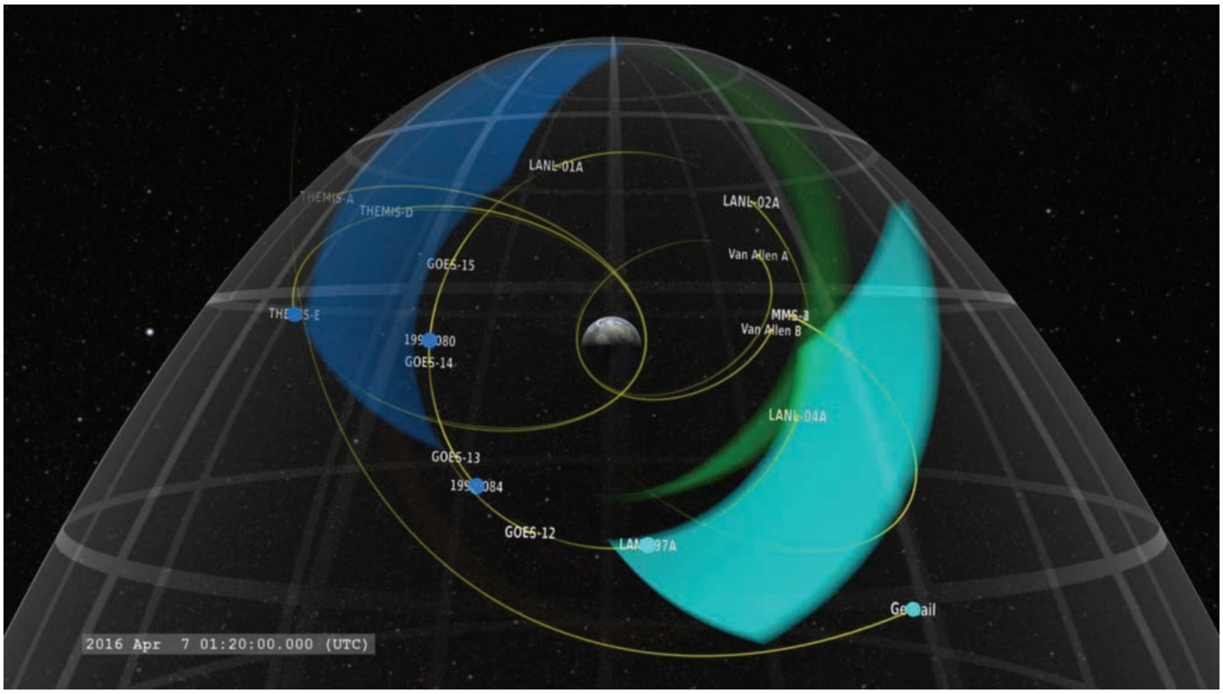

FIGURE C-5 Three energetic particle injections, shown with the three colors, tracked by an array of spacecraft through the global magnetosphere.
SOURCE: NASA's Scientific Visualization Studio.

- *Energetic particle acceleration:* Modeling studies, constrained by data from missions including THEMIS and MMS, have discovered that coherent dipolarization fronts or dipolarizing flux bundles can carry energetic electrons and ions earthward by trapping them in drifts around localized "magnetic islands." This may play an important role in the energization and transport of particles from the tail into the inner magnetosphere.
- *Structure of the substorm current wedge:* New results from THEMIS, ground-based magnetometers, and all-sky imagers (ASIs), and models over the past decade have introduced multiple conflicting hypotheses for the structure of the large-scale substorm current wedge, the electrical current system that connects the magnetosphere to the ionosphere. The hypotheses include that it is one large system, as previously thought; that it originates from the pileup of multiple mesoscale structures; and/or that it is composed of multiple "wedgelets" that form simultaneously and continuously. These models provide advancement in understanding but also motivate some of the science questions for the next decade.
- *Solar wind-magnetosphere coupling beyond Earth:* New results from the Mars Atmosphere and Volatile Evolution (MAVEN) mission at Mars and Juno at Jupiter have provided evidence of magnetic reconnection at the dayside crustal magnetic fields and the planet's dayside magnetopause, respectively. Conversely, new theoretical studies of the Ice Giants, Uranus and Neptune, suggest that the nature of the solar wind–magnetosphere coupling of these worlds may be driven more by viscous-like interactions rather than reconnection.
- *Magnetotail dynamics beyond Earth:* Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) provided the first direct observation of substorm-related impulsive injections of electrons at Mercury. Likewise, reanalysis of Voyager 2 observations at Uranus found evidence of a tailward-directed plasmoid likely resulting from magnetotail reconnection.

C.1.4 Magnetosphere–Ionosphere–Thermosphere Coupling

The magnetosphere and ionosphere/thermosphere are coupled through a myriad of processes that affect the dynamics of both regions, as illustrated in Figure C-6. These processes occur on a range of spatial and temporal scales, with the possibility of cross-scale coupling; for example, long-term/global-scale processes affecting the development of shorter-duration/small-scale phenomena, and vice versa. Major progress has been made in understanding the transfer of mass, momentum, and energy between the magnetosphere and ionosphere/thermosphere.

Significant achievements and landmark discoveries over the past decade include the following:

- *Kinetic and electromagnetic energy deposition in the ionosphere and thermosphere:* Patchy processes with transverse scales in the topside ionosphere ≲100 km can be associated with extreme Poynting fluxes >170 mW/m^2. There is an ongoing debate on the importance of these processes relative to larger-scale

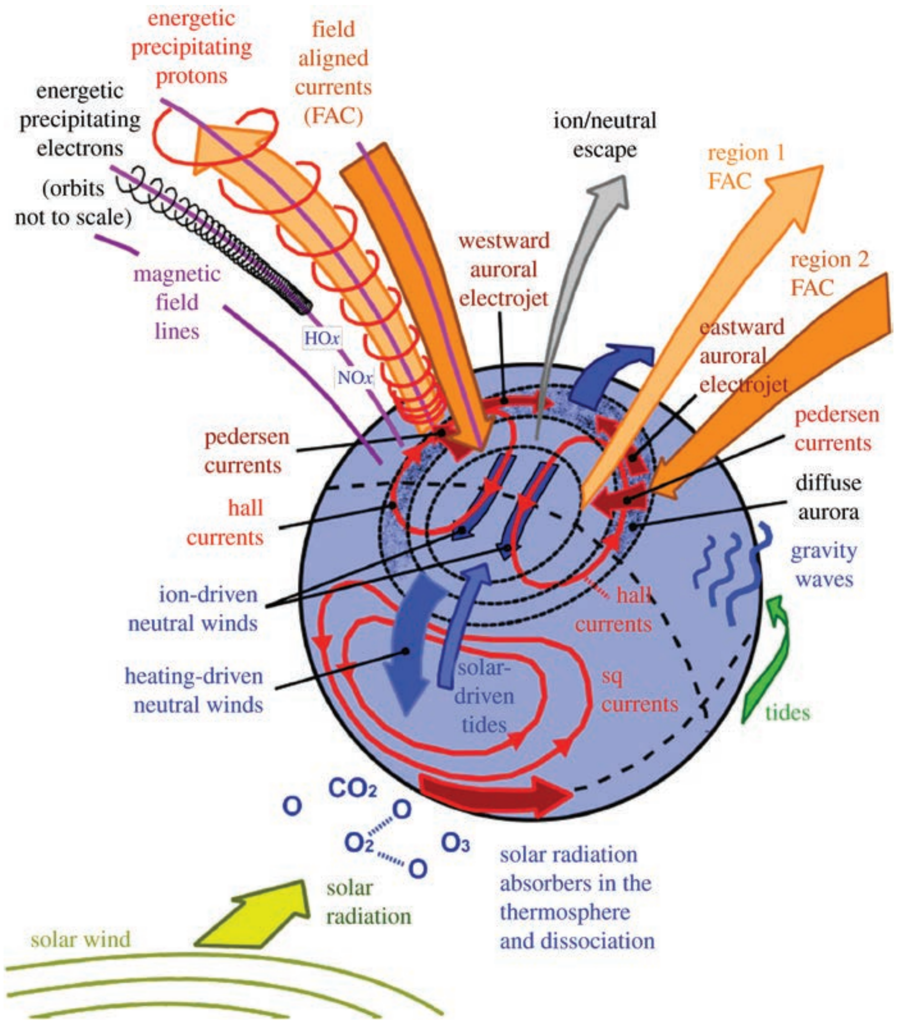

FIGURE C-6 Overview of the coupling between the ionosphere/thermosphere region and the magnetosphere.
SOURCE: Used with permission of The Royal Society (United Kingdom) from T.E. Sarris, 2019, "Understanding the Ionosphere Thermosphere Response to Solar and Magnetospheric Drivers: Status, Challenges and Open Issues," *Philosophical Transactions of the Royal Society A* 377(2148):20180101, http://doi.org/10.1098/rsta.2018.0101; permission conveyed through Copyright Clearance Center, Inc.

processes in determining global energy deposition rates, heating, and dynamics. In addition, it was shown that substantial electromagnetic/kinetic energy input and related ionosphere–thermosphere heating can occur outside major geomagnetic storms and at a range of altitudes. This high-latitude energy deposition can alter thermospheric wind circulation and lead to thermospheric composition change, which then affects the ionospheric density.

- *Multiscale electrodynamic and mass coupling:* The occurrence of dramatic enhancements in mid-latitude ionospheric convection flows are linked to the occurrence of an optical emission called STEVE (strong thermal emission velocity enhancement) and finally to structured flows and waves in the magnetosphere. In addition, the penetration and shielding electric fields from the magnetosphere during geomagnetic storms play a crucial role in the formation and evolution of the ionospheric density structures, such as the storm-enhanced density (SED) plumes and polar cap patches. These high-density structures have been shown to supply large fluxes of ionospheric heavy ions to the magnetosphere, which in turn can affect the magnetospheric dynamics, such as reconnection and ring current ion composition.
- *The causes and consequences of north-south and east-west asymmetries:* It was found that asymmetries dramatically alter the nominal structure of ionospheric convection patterns, large-scale current systems, wave activity, and geomagnetic disturbances. The sources of asymmetries include Earth's offset dipole, seasonal variations in solar illumination leading to north-south hemisphere asymmetries in high-latitude energy deposition and ionospheric conductance, and asymmetries in solar wind driving conditions imposed on the magnetosphere–ionosphere system.
- *Imaging magnetospheric processes with the aurora:* New abilities to remote sense the magnetospheric dynamics using the aurora have been unlocked through analyzing the connections between magnetospheric processes, energy and species-dependent particle precipitation, and multiwavelength aurora. For example, discoveries have linked pulsating and diffuse aurora to a range of plasma wave dynamics in the inner magnetosphere.
- *A new era of understanding magnetosphere–ionosphere coupling at Jupiter:* The Juno mission provided the first in situ investigations of the poles of Jupiter. This revealed the presence of phenomena-like ion conics similar to those seen at Earth, but with others much more extreme, like megavolt electric potentials. These results have opened new debates as to whether these extreme polar acceleration regions may actually serve as a source of Jupiter's extreme radiation belts.

C.2 PRIORITY SCIENCE GOALS FOR MAGNETOSPHERIC PHYSICS

Section C.1 highlights the tremendous progress that has been made in the past decade, particularly in understanding the dynamics of the radiation belts and the microphysics of magnetic reconnection. But the past decade has also revealed areas with significant open questions. First, it has become apparent that that the coupling between systems in the magnetosphere affects the global dynamics. While substantial previous work has focused on understanding the behavior in specific regions—such as the inner magnetosphere, the magnetotail, the magnetopause boundary, or the low-altitude auroral zone—each of these regions interacts with and affects the rest of the system. The links between these systems are in many cases not well understood. It has also become clear that much of the important dynamics are occurring at scales that are not well sampled. Most of magnetospheric dynamics is driven by magnetic reconnection-associated processes at the magnetopause and in the magnetotail. While the global scales of this interaction are understood, and the microscales have now been explored in detail with MMS, it is not yet understood how the microscale processes are initiated and how the regions around them evolve, ultimately leading to the observed global-scale dynamics.

It has also become evident that the contribution and impacts of the ionospheric source to the magnetosphere is not well understood. There is a cold ion component that dominates the density in much of the magnetosphere but is difficult to measure and so has not been well characterized. The processes that lead to outflow of the ionospheric plasma at different latitudes, how these processes vary with the energy input, and how this variation affects the energy distribution and composition of both the cold and hot components of the outflow still has many aspects that are not known. Furthermore, the impacts of these cold and hot components on various magnetospheric processes, such as WPIs, reconnection, and storm-time dynamics remains to be quantified.

The fundamental question of how particles are accelerated and heated throughout the magnetosphere is only partially resolved. While progress has been made in understanding the acceleration of the radiation belts, and acceleration by reconnection, there is still much that remains unknown.

Last, while Earth provides one example of a magnetosphere, exhibiting dynamics under one set of conditions, other planets provide a wide variety of characteristics that can be used to understand how magnetospheres operate universally. Many of these planets are largely unexplored.

Based on this assessment of unknowns, the panel has framed the following six questions:

1. How is the solar wind energy input to the magnetosphere transmitted between different regions and across different scales?
2. What are the characteristics, life cycle, and magnetospheric impact of plasma of ionospheric origin—both the cold populations and hotter energetic outflows?
3. What controls the multiscale electrodynamic coupling between the ionosphere and the magnetosphere?
4. What are the 3D global properties of turbulence, magnetic reconnection, and shocks, and what is their role in coupling energy in the magnetosphere?
5. How are particles accelerated throughout planetary magnetospheres?
6. How do other planets' magnetospheric characteristics and configurations affect their magnetospheric processes, interactions, and dynamics?

All these questions are critical for the understanding of magnetospheric dynamics. For the next decade, the first four questions are prioritized. The sixth question, focusing on understanding the magnetospheres of other planets, is a longer-term goal. While there are aspects of this question that can be addressed in the next decade, fully exploring magnetospheric dynamics under all the different conditions represented by other planets requires significant resources beyond what is possible in the next decade. While the general topic of acceleration is not a focus for the coming decade, some important aspects of question 5, targeting particle acceleration, are included under the other questions: in particular, acceleration of ionospheric ions to create ion outflow is included in question 2, and acceleration and heating through reconnection, turbulence and shocks is included in question 4, and dynamics of radiation belts in other systems such as Jupiter is included in question 6. Investigations into all aspects of acceleration in the magnetosphere are still supported. Here the four PSGs are discussed in detail.

C.2.1 Priority Science Goal 1: How Is the Solar Wind Energy Input to the Magnetosphere Transmitted Between Different Regions and Across Different Scales?

The magnetospheric community has answered aspects of this question on global scales—that is, scales that span the width of the magnetotail—and has begun investigating how this occurs on meso-scales and small-scales as well. See Table C-1 for examples of global versus meso-scales in phenomena on Earth's nightside and Table C-2 for scales on the dayside. Note the scale sizes are defined the same for dayside phenomena. But the results show that significant processes are occurring at spatial scales that are not yet resolvable with current measurements. These processes must be better understood to fully appreciate the complex dynamics. In addition, there are major gaps in the understanding of how energy, momentum, and mass are distributed, because geospace is comprised of several interconnected regimes that display a broad range of spatial scales and response times, and interact with each other with various degrees of feedback, hysteresis, and other aspects characteristic of complex systems. The barrier faced in achieving true system science progress is the lack of a coordinated program that can answer how energy, mass, and momentum are transferred *between* different regions of the solar wind–magnetosphere–ionosphere coupled system with sufficiently granular resolution to accommodate the broad range of space and timescales involved. Specific objectives required to make progress are given in Table C-3.

Much of the energy that drives geomagnetic and ionospheric disturbances and dynamics is extracted from the flowing solar wind and distributed throughout geospace. Over the past decade, while significant progress has been made in understanding the processing of plasma and flow of energy from the solar wind into the magnetosphere, clear gaps in understanding have emerged. The community has come to the consensus that magnetic reconnection

TABLE C-1 Examples of Global Versus Mesoscale Phenomena on Earth's Nightside

Phenomena	Spatial Size	Temporal Size	Additional Description
Dipolarization	Several hours MLT	Tens of minutes to >hour	Persistent magnetic field increase toward more dipolar; historical substorm indicator in the tail
Dipolarizing Flux Bundles	~1–several R_E (in Y_{GSM})	Single DFB: ~40s; Train of DFBs: minutes (at satellite)	Temporal or spatial increases in Bz; typically associated with fast plasma flows
Dipolarization Front	~500–1,000 km (in X_{GSM})	Seconds (at satellite); minutes to tens of minutes	Increase in Bz preceding a DFB; separates hot plasma inside DFB from cooler surrounding plasma
Substorm Current Wedge	Several hours MLT	Tens of minutes to >hour	Current diversion from the tail through the ionosphere; based on ground and space observations
Wedgelets	~1–several R_E in azimuth (~Y_{GSM})	Single: ~40s; Train: minutes (at satellite)	Temporally or azimuthally localized wedge indicators; related to mesoscale flows
Global Aurora	>1,000 km, can span few hours MLT	Tens of minutes to hours	Auroral oval, large-scale diffuse and discrete aurora
Mesoscale aurora	~10 km–500 km	Minutes to tens of minutes	Streamers, poleward boundary intensifications, etc.
Substorm Injection	Up to several hours MLT	Tens of minutes to >hour	Persistent energetic particle flux increases; historically at GEO
Mesoscale Injections	~1–several R_E	Tens of seconds (single) to minutes (at satellite)	Temporal energetic particle flux enhancements; observed in the near tail and inner magnetosphere

NOTE: Acronyms defined in Appendix H.
SOURCE: Gabrielse et al. (2023), https://doi.org/10.3389/fspas.2023.1151339. CC BY 4.0.

TABLE C-2 Examples of Mesoscale Phenomena on Earth's Dayside

	Hot Flow Anomalies	Spontaneous Hot Flow Anomalies	Foreshock Bubbles	Foreshock Cavities	Foreshock Cavitons	Foreshock compressional Boundaries	Density Holes	Short Large-Amplitude Magnetic Structures
Duration	Tens of seconds to minutes	Tens of seconds to minutes	Tens of seconds to minutes	Tens of seconds to minutes	Tens of seconds to ~1 minute	Tens of seconds to minutes	Seconds to ~1 minute	Seconds to tens of seconds
Scale size	~1 to a few R_E	~1 to a few R_E	~1 to a few R_E	~1 to a few R_E	~1 to a few R_E	~1 to a few R_E	~1 to a few R_E	Up to 3,000 km

SOURCE: Zhang et al. (2022), https://doi.org/10.1007/s11214-021-00865-0.

TABLE C-3 Objectives for Priority Science Goal 1

Priority Science Goal (1 of 4)	Objectives
How is the solar wind energy input to the magnetosphere transmitted between different regions and across different scales?	**1.a.** Determine the spatial scale size and extent and the temporal evolution of energy and mass transfer processes at the magnetopause.
	1.b. Determine how processes at different spatial scales (kinetic versus meso- versus global scales) transport, store, and release energy in the nightside plasma sheet and into the ring current.
	1.c. Determine the connection between multiscale structures in the plasma sheet and discrete structures in the aurora.

is the primary mechanism for the transfer of energy into the magnetopause, yet it is unknown how this process presents itself spatially across the magnetopause. Under what conditions is reconnection spatially localized versus spatially extended? The spatial extent is closely linked to how much energy is being transferred from the solar wind at any given time. Other structures, such as boundary waves, and boundary conditions within the magnetosphere have also been found to impact the coupling and flow of energy, but their relative importance remains unknown. The role the magnetosphere and its internal plasma populations may play in modulating dayside reconnection remains a major open topic. These gaps in understanding are linked by a common thread: the cross-scale coupling of physics, specifically the link between spatial scales coupling ion- to MHD-scale physics.

In the magnetotail, it is known that after reconnection, most of the magnetic flux is transported via mesoscale (roughly 1–3 R_E) fast plasma flows. Those flows and their magnetic structures have been extensively observed and modeled throughout the plasma sheet, but the transition points remain unclear. It is not known what initiates the magnetotail reconnection that starts these meso-scale flows, and what determines their scale size. When those flows reach Earth's "transition region," the region between ~6 R_E to 12 R_E downtail where Earth's magnetic field transitions from dipolar to stretched field lines, it is not understood how that energy is transmitted: how much goes to the inner magnetosphere, how much is sent to the ionosphere, and how much slides around to the dayside.

To address this question, the primary transition points of interest are therefore the boundary between the solar wind and the magnetosphere (e.g., the magnetopause) to better understand energy transfer from the solar wind to the magnetospheric system, the transition from the plasma sheet to the inner magnetosphere to better understand how the tail supplies the radiation belts and ring current with particles and energy, and the connection between the magnetosphere and the ionosphere as a coupled system.

Current Research Activity

Operating and Past Missions

Many serendipitous spatial arrangements of current (and past) assets have been used to probe how energy is transmitted. For example, the THEMIS mission observed the dipolarization fronts and meso-scale flows that contributed to magnetic flux, particle, and energy transport toward the inner magnetosphere. The three THEMIS satellites closest to Earth have been used to try to constrain particle injection sizes and propagation directions in conjunction with NASA's Van Allen Probes, Magnetospheric Multiscale Mission (MMS), Japan Aerospace Exploration Agency's (JAXA's) Arase satellite, and LANL and/or GOES satellites at geosynchronous orbit (6.6 R_E). Ground-based assets have also been used with these missions, using auroral, riometer, and radar signatures to indicate where the plasma flows and particle injections may be occurring. Even with approximately sixteen satellites serendipitously located to study one event, injection characteristics were difficult to constrain.

Particle transport and heating has also been studied using conjunctions between in situ observations from NASA's MMS mission and remote observations from the energetic neutral atom (ENA) spectrometers aboard NASA's Two Wide-Angle Imaging Neutral-atom Spectrometers (TWINS) mission. The TWINS ENA data have been creatively mapped to the plasma sheet to provide a 2D view of the heated plasma flows and compared to MMS data. At a few-minute cadence, however, understanding of temporal evolution is limited. Similarly, NASA's Interstellar Boundary Explorer (IBEX) provided ENA imaging of the bow shock and magnetosheath to study the energy input into the magnetosphere system. For example, ENA imaging of the plasma sheet location and shape out to ~16 R_E showed a possible tail disconnection event at ~10 R_E on the nightside and the bow shock, foreshock, and subsolar magnetopause on the dayside. These ENA images provide context for large-scale structures and global dynamics in the magnetosphere in response to varying solar wind conditions, but the temporal and spatial scales required by this mission (many days) are not sufficient to study dynamic processes at meso-scales.

As a tetrahedron of satellites with separation distances that have ranged from 600–20,000 km, the European Space Agency (ESA) Cluster mission has made great strides in studying how meso-scale structures in the magnetosphere (on the order of 1–3 R_E wide) propagate and what their scale sizes are. Cluster has measured the propagation direction and speed of dipolarization fronts at one location but is unable to follow the same magnetic structure along its evolution. Moreover, Cluster studies on this topic are limited as the spacecraft orbits only rarely pass through Earth's transition region. The ability to follow the same magnetic structure along its evolution would help ascertain where and how the material and energy are transported. Was the magnetic structure/flow channel stopped before it could deposit energy, particles, and momentum in the inner magnetosphere? Did it deposit its information at the boundary of the transition region?

As a tetrahedron of satellites with tens of km separation distances, MMS has revealed kinetic-scale physics—especially related to reconnection—more than any other mission before it. HelioSwarm, a NASA Medium Class Explorer (MIDEX) mission currently in early development, will look at how energy is transferred across different scales. Although its primary focus is the solar wind, it will also spend time in the magnetosphere where it can probe magnetospheric turbulence. With apogee at almost lunar distances and perigee near 15 R_E, HelioSwarm will not directly study the energy/mass/momentum transfer from the solar wind to the magnetosphere nor from the plasma sheet to the inner magnetosphere (or ionosphere).

Another mission in development to measure the solar wind and its dynamic interaction with the magnetosphere is the Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) mission, a joint effort between ESA and the Chinese Academy of Sciences (CAS). Expected to launch in 2025, SMILE will observe the solar wind interaction with the magnetosphere with its X-ray and ultraviolet cameras, gathering simultaneous images and videos of the dayside magnetopause, the polar cusps, and the auroral oval. SMILE will also host an ion analyzer and a magnetometer to monitor the ions in the solar wind, magnetosheath and magnetosphere while detecting changes in the local magnetic field.

The Electrojet Zeeman Imaging Explorer (EZIE) mission, planned for launch in early Fall 2024, will address the topic of energy, mass, and momentum transport between the magnetosphere and ionosphere by obtaining remote observations of the structure of the electrojet currents in the ionosphere to help distinguish between multiple published hypotheses of the structure of the substorm current wedge originating in the magnetotail.

NASA's Geospace Dynamic Constellation (GDC) mission, which is currently planned for launch no earlier than 2028, will lead to a better understanding of magnetosphere–ionosphere–thermosphere coupling. GDC will address crucial scientific questions pertaining to the dynamic processes active in Earth's upper atmosphere; their local, regional, and global structure; and their role in driving and modifying magnetospheric activity. Leveraging a constellation of spacecraft to enable simultaneous multipoint observations, GDC will be the first mission to address these questions on a global scale. This investigation is central to understanding the basic physics and chemistry of the upper atmosphere and its interaction with Earth's magnetosphere, but also will produce insights into space weather processes. GDC mission goals therefore fit very well under this scientific objective, and the timely development and launch of GDC is strongly supported.

Ground-Based Facilities

Ground-based observatories have been instrumental in making immense contributions to this PSG. On Earth's dayside, Super Dual Auroral Radar Network (SuperDARN) radar stations have captured poleward-moving meso-scale flows that form after dayside reconnection. Ground-based magnetometers have also measured localized transients and activity indices. A combination of SuperDARN radars and ASIs have viewed related ionosphere flows and auroral forms as they propagate from the dayside across the polar cap and through the auroral oval. ASIs and incoherent scatter (IS) radars have captured the energy flux input from precipitating magnetospheric particles and estimated the related conductance, showing that meso-scale features contribute an important (sometimes the majority) fraction of the precipitating energy flux. These magnetospheric drivers have major impacts on the ionosphere–thermosphere (IT) system (e.g., the neutral winds and neutral densities) and the ionosphere itself can influence the magnetosphere directly or via feedback mechanisms (e.g., conductance enhancements). IS radars also measure convection, field-aligned flows, altitudinal conductivity profiles, and energy deposition in three dimensions. The Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) gives continuous observations of global field-aligned current systems.

From these and other disparate missions and programs, it is known that meso-scale phenomena are critical to the energy, mass, and momentum flow into, within, and out of the magnetosphere. It is known that meso-scale flux transfer events are important on Earth's dayside for transporting magnetic flux from the dayside to the nightside. But details are still unknown.

Theory, Modeling, and Simulations

State-of-the-art models are just now achieving the meso-scale resolution required to address this science priority and are also working to couple different regions of geospace. Two-way coupled models are necessary to capture the important feedback effects that occur in a coupled system. In the patchwork model of models approach, the nightside transition region (6–12 R_E) is typically treated as the overlap of ideal MHD in the stretched tail, which excludes drift kinetic physics, and an inner magnetosphere model, which assumes slow flow and equilibrated flux tubes. In other words, two incomplete models are combined with the hope to approximate the result of a self-consistent model. The lack of a self-consistent treatment of the transition region limits not only the ability to understand the coupling between the magnetotail and inner magnetosphere, but also a critical feedback loop spanning the magnetosphere, ionosphere, and thermosphere. The challenge of modeling the transition region is that this requires both highly resolved spatial scales over geospace timescales of several days and kinetic physics that goes beyond the typical ideal fluid treatments currently used. While the ideal fluid treatment is the simplest physical description typically used, capturing the role of mesoscale processes on the global geospace system in a model or two-way coupling of kinetic and fluid models has only become possible in the past decade and remains quite challenging. As an example, the self-consistent global modeling of mesoscale auroral forms, like auroral beads, pushes MHD-based geospace models to their highest resolution capabilities.

How Does the Current Research Activity Motivate the Goal?

To make progress in understanding these processes requires observations, either in situ or remote, that capture phenomena occurring nearly simultaneously throughout the magnetosphere as well as coupled models with high enough resolution to capture the dynamic evolution of the magnetosphere. Past and current missions have provided insight to the benefits and progress that can be made when coordinated, multispacecraft missions are designed to address a specific open question. It goes without saying, however, that the magnetosphere is very large and very wide. To constrain the particle and energy transport mechanism through the transition region, for example, requires a 2D view in both azimuth and radial distance. The magnetospheric community has been creative in using the HSO to study events in an ad hoc way when satellite orbits and ground-based observatories align by chance. However, fortuitous conjunctions are limited in scope and frequency, making it difficult to fully understand how particles and energy are transported without a planned program.

In terms of modeling, approaches aimed at advancing beyond ideal MHD, including global Hall MHD, embedded particle-in-cell (PIC), global hybrid, Vlasov and multifluid-Maxwell, impose enormous computational costs currently forcing trade-offs like reduced dimensionality, resolution degradation or limited duration. For example, a recent 3D global magnetosphere hybrid-Vlasov simulation required 15 million core hours per 25 minutes of model time.

The current research activity motivates this PSG by revealing the importance of understanding the coupled magnetosphere system. Capturing and understanding the transfer of energy, mass, and momentum at scales smaller than global from the solar wind, throughout the magnetosphere, and into the ionosphere has to date been left to serendipitous conjunctions between disparate satellite missions and ground-based programs that have limited the ability to understand the system as a whole. Improving on the current activity requires a system observatory infrastructure with better coordination to go after the most pressing science objectives. Addressing the goal requires coordinated observations and modeling with detailed physics (beyond ideal MHD, e.g., including the Hall term and kinetic physics) with spatial resolution capable of fully simulating meso-scale structures over typical geospace timescales. (See Table C-2.) The focus of these observations and modeling needs to be of the "transition regions" within geospace—that is, the dayside where solar wind impinges on the magnetosphere, the magnetic field transition region between the magnetotail plasma sheet and the inner magnetosphere (including the radiation belts and ring current), and the connection between the magnetosphere and ionosphere.

C.2.2 Priority Science Goal 2: What Are the Characteristics, Life Cycle, and Magnetospheric Impact of Plasma of Ionospheric Origin—Both the Cold Populations and the Hotter Energetic Outflows?

There are two sources of near-Earth plasma: the external source from the Sun, including the solar wind and solar energetic particles, and the internal source provided by the planet's atmosphere. Modeling and observations have shown that both sources play a role, with the ionosphere becoming more important during active times, but there are still many questions regarding where and when the different sources dominate, and what their pathways are through the magnetosphere. Accurate identification of the source of the protons, the dominant species in the magnetosphere, is challenging because protons are the primary constituents of both the solar wind and the high-altitude ionospheric plasma. However, the two sources differ in both their energy distribution and their composition, and these can be used to infer the source. While the solar wind plasma is on average 96 percent H^+, the ionospheric plasma that escapes into the magnetosphere can have a significant fraction of singly charged heavy ions, predominantly O^+ and N^+. Tracking singly charged heavy ions can provide insights into the dynamic linkage between the ionosphere and solar wind, as well as clues regarding the generalized ionospheric outflow and its role in affecting the ionosphere–magnetosphere system. While both the solar wind and the ionospheric plasma can contribute to the hot (>0.5 keV) plasma, plasma from the ionospheric source can also be cold. Tracking this cold population also provides information on the ionospheric source, including its acceleration and transport throughout the magnetosphere.

Owing to the cross-scale, cross-regime, and cross-energy nature of the circulation and energization processes affecting plasma of ionospheric origin, and because of the challenges in measuring the lowest-energy (<eV) ions and electrons, this plasma life cycle remains poorly understood. Determining the physical processes acting in distinct regions along the transport paths of the ionospheric ions will enhance the overall understanding of the characteristics, and lifecycle of the plasma of ionospheric origin, and reveal the impacts on the global magnetosphere dynamics. Specific objectives related to PSG 2 are given in Table C-4.

The plasmasphere is a vast reservoir of cold (~<1 eV) plasma in the inner magnetosphere with densities that can be more than 1,000 cm^{-3}, orders of magnitude larger than densities for particles at higher energies. The source of cold plasma is primarily direct outflow from the ionosphere, with some contribution from charge exchange of more energetic ions with the neutral hydrogen geocorona. Plasmaspheric density and composition can play critical roles in wave generation and propagation, WPIs, and energetic particle scattering, and so the dynamics of this population affects many other aspects of the magnetospheric system. There are still many unknowns regarding the physics of plasmaspheric erosion and refilling. There are still fundamental questions regarding the physics that controls the outflow at the field line footpoint, and how the outflowing particles become trapped. Theoretical and modeling efforts demonstrate difficulty in explaining the observed refilling rates, which can vary from a few to hundreds of particles per cubic centimeter per day.

TABLE C-4 Objectives for Priority Science Goal 2

Priority Science Goal (2 of 4)	Objectives
What are the characteristics, life cycle, and magnetospheric impact of plasma of ionospheric origin—both the cold populations and hotter energetic outflows?	**2.a.** Determine how the plasmasphere forms and evolves.
	2.b. Determine what drives ion outflow, and by what pathways the ionospheric-source plasma moves throughout the magnetosphere.
	2.c. Determine the impacts of ionospheric plasma on the magnetosphere.
	2.d. Determine the ultimate fate of ionospheric-source plasma.

While light ion (H^+ and He^+) outflows, including those that form the plasmasphere, can be primarily explained by classical polar wind theory, the more energetic outflows observed in the auroral zone, including the outflow of heavy ion species (N^+, O^+, and molecular species NO^+, N_2^+, and O_2^+), are more complicated because they require additional energy to overcome Earth's gravitational potential. Several mechanisms have been identified that can combine to accelerate the ions including: upwelling from low-altitude frictional heating, heating of ionospheric electrons by soft electron precipitation, enhancement of the ambipolar electric field, transverse heating of ions through WPIs, ponderomotive forces of Alfvén waves or field aligned currents (FACs) driving the parallel electric field, and centrifugal acceleration owing to field line convection and curvature changes. These resulting ionospheric outflows can be either transported into different regions of the magnetosphere (e.g., plasma sheet and tail lobes) or can be lost to space on polar field lines connected to the interplanetary magnetic field. In situ observations have revealed the presence of ionospheric plasma throughout the magnetosphere, extending more than 200 R_E down the tail. Still, many questions remain on the interplay of the heating and acceleration processes at different altitudes responsible for transporting heavy ions throughout the magnetosphere.

How heavy ions impact magnetospheric dynamics remains an active research topic. It is still uncertain whether heavy ions facilitate or inhibit the occurrence of substorms in the magnetotail, and how they impact the unloading during tail reconnection. Recent observations show that cold and heavy ions can slow the local dayside reconnection rate, but how much global dynamics are impacted is not known. The cold ions and electrons in the inner magnetosphere can change wave properties and energy transfer via WPIs in multiple ways, but the lack of cold ion and electron distribution functions, as well as cold ion composition measurements, has made detailed comparisons between observations and theory difficult.

The study of the escape of ionospheric ions has a broader impact, as well. Leveraging the understanding of charged particle acceleration, heating, transport, and circulation throughout the terrestrial environment, can provide clues about atmospheric loss at geological scales, and can aid in identifying the characteristic attributes of planet-star pairs that support habitability. Several mechanisms have been invoked to explain planetary atmospheric loss. For present-day Earth, thermal escape of neutrals is limited to only the lightest elements like hydrogen and helium. However, oxygen and other heavy species can escape into interplanetary space as ions after gaining sufficient energy to overcome the gravitational potential. Therefore, ionospheric outflow provides a pathway for atmospheric migration and escape at a rate that generally depends on the solar wind interaction with the planetary magnetic field. Notably, this process occurs without necessitating direct interaction with the solar wind.

Current Research Activity

Operating and Past U.S. and International Missions

Over the past decade, growing evidence has supported the hypothesis that cold plasma populations in the magnetosphere play a pivotal role in driving the system's dynamics, highlighting the need to understand the sources of cold plasma in the near-Earth region, their pathways and impacts. Several missions, both recent (e.g., Van Allen Probes, TWINS) and historical (e.g., the Imager for Magnetopause-to-Aurora Global Exploration [IMAGE] mission, Polar) have contributed to the current knowledge of the various processes and components making up this system. However, in situ measurements of the cold (~1 eV) plasma are difficult to make; a positive spacecraft potential often prevents these ions from reaching the spacecraft, while negative spacecraft potential and/or photoelectron contamination can complicate cold electron measurements. The last instrument dedicated to measuring the composition of cold ions was carried on Dynamics Explorer 1 (DE-1), which included an aperture bias to overcome the spacecraft potential. Cluster also carried a plasma instrument with a low energy mode to measure the higher-energy tail of the plasmasphere particle distribution. Similarly, Van Allen Probes measured down to 1 eV. While the density calculated by Van Allen Probes using the lowest energy measurements does approximately track the plasmaspheric density, it is about a factor of 40 lower.

To capture the full plasma population, indirect measurement techniques are often used. The spacecraft potential or the upper hybrid resonance frequency are used to estimate the total plasma density but give no information on composition or energy and angular distribution. The IMAGE mission measured the extreme ultraviolet (EUV) distribution of He+, thus revealing the entirety of the plasmasphere and providing insight into the global structure and evolution of the plasmasphere and its mesoscale features, such as plasmaspheric plumes, shoulders, and notches. However, determining the full density from these images requires assumptions about the composition. Ground- and space-based measurements of field line resonances have been used to determine the mass density distribution of the plasmasphere statistically; these can be combined with measurements of the total density from the spacecraft potential or upper hybrid line to determine the average mass. Still, there is much that has not been measured, even for the plasmasphere, the densest of the cold plasma populations.

The plasmasphere is not the only location where a hidden cold population may be present. The Cluster spacecraft identified a cold ion population in the lobe region using measurements of a perturbation in the electric field measurement owing to a wake caused by cold plasma flow around the spacecraft. In the magnetotail, another cold ion population was identified when a spacecraft charged negatively while in eclipse. Similar cold ion populations have also been observed during eclipses on geosynchronous spacecraft. The importance of these cold populations outside the plasmasphere are only now starting to be explored.

Hotter ionospheric plasma is easier to measure–instruments on Fast Auroral SnapshoT (FAST), Cluster, Polar, Van Allen Probes and MMS all measure ions from ~10 eV to ~40 keV with moderate mass resolution. All are able to distinguish H^+, He^+ and the CNO group. The combination of FAST measurements of outflow at ~4,000 km altitude, Cluster measurements over the polar cap and into the lobe and plasma sheet, MMS measurements in the equatorial plasma sheet and Van Allen Probes in the inner magnetosphere has provided an extensive database of ion measurements for *statistically* tracking the transport paths of ions through the magnetosphere. In addition, ENA imaging from both IMAGE and TWINS have provided a global perspective on the evolution of ions in the inner magnetosphere during storms, including differences in H^+ and O^+ behavior.

There are fewer measurements available for determining the processes that affect outflow at different altitudes and latitudes. Measurements from FAST, Akebono, Polar, and Cluster, have provided insights into various facets of ion outflow across distinct altitudes, albeit usually not concurrently. Sounding rockets have made substantial contributions to the current understanding of ion heating occurring at lower altitudes and the physical processes driving ionospheric outflow. For instance, the Sounding of the Cleft Ion Fountain Energization Region (SCIFER) experiment probed the origins of the Cleft Ion Fountain at altitudes of ~1,000–2,000 km, while the Magnetosphere–Ionosphere Coupling in the Alfvén Resonator (MICA) sounding rocket observed particle distributions below 325 km that constitute the primary source of the ion outflow. Other rocket experiments, such as Visualizing Ion Outflow via Neutral Atom Sensing (VISIONS-1, -2, and -3), have provided insight into the possible mechanisms responsible for the cusp ion outflow via ENA imaging and in situ particle measurements. These platforms can probe lower altitudes in complement to spacecraft observations. However, the measurements necessary to both identify the heating mechanisms that bring ionospheric ions above the exobase and illuminate the altitude dependence of acceleration that brings the more energetic ions into the magnetosphere are missing.

Ground-Based Facilities

Ground-based facilities play a crucial role in tracking plasma of ionospheric origin. IS radars are particularly effective ground-based tools for profiling the ionosphere from the D-region to the exobase and provide high-resolution measurements of quantities fundamental for specifying low-altitude boundary conditions for spacecraft measurements and mass extraction models. Existing IS radar facilities operate in the auroral zone (i.e., Poker Flat), in the cusp/cleft and polar cap boundary zones (i.e., Svalbard), and in the polar cap (i.e., Resolute Bay).

Altitude profiles provided by IS radar measurements can be used to derive parameters that are not possible through single-point measurements. By employing smooth curve fittings to these IS radar altitude profiles, it becomes possible to evaluate quantities that require derivatives or integrals of the plasma state parameters, like the ambipolar electric field, the divergence of the upflow number flux, the ion pressure gradient, and electron heat flux associated with thermal conduction. Smooth curve fittings applied to topside profiles enable the extrapolation of IS radar-derived profiles to spacecraft altitudes. Comparisons of these extrapolated values to the in situ measurements can then be used to infer the nature of additional acceleration occurring in the intermediate region between the highest IS radar measurements and the spacecraft positioned at higher altitudes.

Additionally, IS radar data can be used to quantify Joule heating and discern its altitude distribution by measuring the Hall and Pedersen conductivities alongside electric fields. Specifying the height distribution of these quantities is relevant to ion outflow science because heat deposited at higher altitudes is more effective at producing F-region upflows. IS radar altitude profiles of the E-region electron density enhancements are useful for estimating the characteristic energy and energy flux of the precipitating electrons. E-region density measurements are instrumental in quantifying the effects of upward field-aligned currents on the generation of outflow.

Beyond the insights garnered from IS radar data, including ground-based measurements derived from magnetometer chains and comprehensive total electron content (TEC) maps provides valuable information regarding the properties and evolution of Earth's plasmasphere. One prominent technique employed in this context is field line resonance, which uses ground-based magnetometer data to infer plasma densities within the magnetosphere. A key factor influencing the accuracy and efficacy of this technique is the density of the ground-based magnetometer networks. Generally, a denser network enhances the reliability and precision of employing field line resonance as an investigative tool. Furthermore, measurements derived from magnetometer chains at different longitudes could constrain the longitudinal plasma mass density.

Last, Global Navigation Satellite System (GNSS) TEC measurements have proven invaluable in delineating the extent and evolution of plasmaspheric plumes. These measurements serve as a complementary resource to in situ observations of cold plasma density.

Theory, Modeling, and Simulations

The past decade marked the departure from the fluid description of ionospheric outflow and the development of novel hybrid approaches. Several numerical models have been developed to transition from a hydrodynamic to a kinetic formalism to include kinetic effects such as WPI. Resonant WPI provides new pathways for ion heating and acceleration, both in the cusp and auroral region, as cyclotron resonance with observed electric field fluctuations leads to the formation of ion conics, features frequently observed above the cusp and auroral regions. However, the wave heating is parameterized based on empirically derived formulas, which include significant uncertainty in the exact altitude profile of the wave power, and temporal variation is not accounted for. Moreover, the wave heating parameter is not dependent on the magnetospheric input, which is an imperfect estimate, but the most accurate one available at present.

A variety of methods including multifluid MHD, individual test particle tracing in MHD fields, and most recently global hybrid codes have been used to model the ion transport from the outflow region through the lobes, into the plasma sheet and into the ring current. There are pros and cons to each method. While significant results showing the impact of O^+ on the global dynamics have been obtained using multifluid approaches, adequately capturing the velocity separation of the outflow population that occurs in the lobes and the nonadiabatic behavior, particularly for O^+, in the magnetotail requires a kinetic approach (beyond the fluid approximation). Increases in computing power are finally making this possible.

Over the past decade, tremendous progress has been made in developing complex frameworks that allow for the exchange of information between global magnetosphere models and those focused on specific regions, such as the polar wind, plasmasphere, ionospheric electrodynamics, and inner magnetosphere. These frameworks enable self-consistent coupling between the plasma and electromagnetic fields and involve different levels of sophistication in modeling collisionless plasma dynamics, ranging from ideal MHD to fully electromagnetic kinetic plasma models (PIC or Maxwell-Vlasov). While these recent developments have been remarkably successful in simulating complex plasma phenomena—such as geomagnetic storms and substorms—and have advanced the knowledge of the effect of ionospheric plasma on the magnetosphere, they still have significant limitations.

The limited cold plasma observations force global magnetosphere models to rely on approximations, assumptions, and empirical relationships for boundary conditions. Therefore, many global and regional numerical models operate on the gross assumption that the ionospheric plasma density is either constant or empirically prescribed and do not include the contribution of heavy ions to the plasma.

Although there are global magnetosphere models that include a cold, dense plasmasphere population or a hotter ring current population, most existing models do not incorporate both the hot and cold populations together in a self-consistent manner. This is a major issue because the plasmasphere holds most of the ionized mass and inertia in the magnetosphere, while the ring current carries most of the energy density. However, observations of cold ions and electrons in the magnetosphere are sparse, in contrast to the more energetic particle populations frequently observed. As a result, progress in developing models for the low energy particle populations has been slow. A functional understanding of plasmaspheric refilling requires, for example, coordinated observations of ionospheric and magnetospheric conditions and significant advancements in numerical modeling.

Understanding the characteristics, lifecycle, and magnetospheric impact of low-energy plasma will advance the understanding of the complexity, coupling, feedback, and inherent nonlinearity of the magnetosphere–ionosphere system. This endeavor requires advances in measuring the neutral density, plasma composition and distribution functions, and simultaneous observations of the magnetospheric energy inputs, to better constrain ongoing modeling efforts.

How Does the Current Research Activity Motivate the Goal?

Recent advancements in modeling and observations have provided us with a better understanding of the various components involved in the circulation of ionospheric plasma through the ionosphere–magnetosphere system. However, there is still a crucial need to link the parts together. In addition to measuring the ionospheric outflow, it is vital to track this plasma as it convects and circulates through the system. These developments have highlighted the benefits of utilizing both heterogeneous and multipoint measurements. For instance, obtaining a global view of the plasmasphere along with simultaneous in situ measurements will constrain plasma density and composition estimates. Additionally, measuring at multiple altitudes can help distinguish between ion upflow and outflow.

C.2.3 Priority Science Goal 3: What Controls the Multiscale Electrodynamic Coupling Between the Ionosphere and the Magnetosphere?

Magnetosphere–ionosphere (M-I) coupling lies at the intersection of many of the science questions important to the understanding of the magnetosphere system, including processes that regulate the transfer of energy from the solar wind to the magnetosphere and processes that regulate ionospheric upflow and ultimately outflow into the magnetosphere. Comprehensive space- and ground-based measurements conducted at Earth have significantly advanced the understanding of the M-I coupling system, and the results have been applied to other planetary M-I systems, as well. Despite those advances, there is an urgent need to expand both observational and modeling capabilities to capture mesoscale (~100–500 km in the ionosphere) processes at sufficient temporal scale ($\lesssim$1-minute cadence) and specify critical physical parameters, such as neutral winds and ionospheric conductance. New results are challenging long-standing assumptions used in modeling and the interpretation of observations including that the ionosphere is a thin-conducting shell, that the northern hemisphere ionosphere is a mirror image of the southern, and that M-I coupling processes can be treated with a quasi-static approximation. While these assumptions have worked well in laying the foundations for understanding of M-I coupling and the development of global models, more sophisticated modeling and comprehensive observational capabilities are needed to move beyond them to account for the dynamic, multiscale processes that play key roles in connecting the ionosphere to the magnetosphere, including during geomagnetic storms.

The overarching science goal can be divided into the four objectives, given in Table C-5.

Current Research Activity

Missions and Facilities Addressing This Goal

While there are no currently flying NASA missions devoted to studying M-I coupling, there are several currently in development that will make significant contributions to addressing part of this priority goal. First, the multisatellite GDC mission would provide unprecedented multiscale I-T measurements and has the appropriate instrumentation to determine the energy deposition and response of the I-T system to energy input from the

TABLE C-5 Objectives for Priority Science Goal 3

Priority Science Goal (3 of 4)	Objectives
What controls the multiscale electrodynamic coupling between the ionosphere and the magnetosphere?	**3.a.** Determine the response of the ionosphere/thermosphere system to magnetospheric and solar wind input as a function of altitude, latitude, and magnetic local time, including asymmetries. **3.b.** Determine how the state of the ionosphere affects magnetosphere–ionosphere coupling. **3.c.** Determine the physical processes controlling the structure and intensity of the global multiscale field-aligned current system. **3.d.** Determine the drivers of the different auroral forms and airglow.

magnetosphere. This strategic Living With a Star (LWS) mission was recommended in the 2013 solar and space physics decadal survey (NRC 2013; hereafter the "2013 decadal survey") and the subsequent midterm assessment, *Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics: A Midterm Assessment* (NASEM 2020), and a pressing need remains for these measurements. This need is even more urgent with the possible decommissioning of the Defense Meteorological Satellite Program (DMSP) satellites in the coming years and expected lack of subsequent energy deposition measurements needed to study M-I coupling. Second, the Electrojet Zeeman Imaging Explorer (EZIE), a SmallSat mission consisting of three satellites in low-Earth orbit (LEO), will provide auroral electrojet measurements using a remote sensing method to probe the poorly sampled ionospheric region where these currents are flowing. By examining electrojet dynamics in this region and under different driving conditions, EZIE will provide new insights into the electrodynamic coupling between the ionosphere and magnetosphere.

There are several other primarily National Science Foundation (NSF)-supported projects with objectives and corresponding measurements that relate to M-I coupling. Most of these projects involve ground-based measurements. Briefly, they include (1) SuperDARN radars that provide multiscale ionospheric flow measurements at 1- to 2-minute cadence, (2) IS radar measurements that provide comprehensive regional ionospheric plasma measurements, and (3) Iridium satellite magnetometer measurements that are used to determine global field-aligned current patterns (AMPERE) at ~10-minute cadence. Alongside these larger projects, there exist many other smaller principal investigator–led projects with a wide range of instrumentation and objectives, including projects involving ground-based magnetometers, ASIs, riometers, and so on. Although these projects provide the observations needed to address this science question, the more coordinated effort described below is needed to fill gaps in instrumentation and spatial coverage to make significant progress. Last, the NSF-supported Madrigal and SuperMAG databases provide essential tools needed to aggregate and access data sets with often widely varying formats.

International collaborations have provided key measurements needed to address this science question. Significant contributions have been made by the ESA Swarm mission and are likely to be made by the upcoming SMILE mission, which will use a combination of imagers and in situ measurements to explore how solar wind driving conditions affect the magnetosphere and high-latitude ionosphere. Ground-based magnetometers and ASIs operated through support from the Canadian Space Agency (CSA) have been essential in providing measurements needed to explore a wide range of M-I coupling processes. The new EISCAT 3D radars will provide unique volumetric measurements needed to probe M-I coupling in 3D. Last, international collaborations are providing key logistical support needed to access high-latitude southern hemisphere regions in Antarctica that are required to examine inter-hemispheric asymmetries; this is likely to become even more important in the next 10 years owing to expected reductions in logistical support by the U.S. Antarctic Program.

Quantifying the energy flow between the solar wind/magnetosphere and the I-T system is essential for holistically understanding energy flow across different geospace regions. This requires measurements of particle precipitation and electromagnetic energy input as a function of altitude, latitude, and magnetic local time (MLT) in both hemispheres. Currently, the DMSP satellites provide limited measurements of precipitating particle energy and Poynting flux into the I-T system at fixed local times, as well as the far ultraviolet (FUV) images of high-latitude regions needed to image the auroral zone from space. It is important to note that these satellites are expected to be decommissioned in the next few years, which will greatly impede efforts to quantify energy deposition. Sounding rocket and balloon investigations have also provided detailed single- and multipoint measurements of these parameters. However, there are no global-scale measurements of these energy flows, which are critically needed as high-latitude drivers of global I-T models. Assuming that Joule heating in the ionosphere equals the input energy, Joule heating and, thus, conductance and convection electric field have often been calculated to estimate the input energy by ignoring neutral winds. However, the lack of global specification of both conductivity and neutral wind distributions at any timescale have introduced considerable uncertainties in quantifying the energy deposition into the I-T system and its response. In terms of the I-T response to energy input from above, there has been a lot of progress on how the ionosphere plasma content, such as the TEC, changes during storms and substorms, mainly owing to the rapidly increasing number of ground-based GNSS receivers, GNSS constellations, and conjunctions with complementary measurements, such as from IS radars and LEO satellites. In addition, understanding of the low and mid-latitude ionosphere and thermosphere responses to energy input during geomagnetic disturbances has been significantly improved by multiple recent missions, including Ionospheric Connection Explorer (ICON), Global-scale Observations of the Limb and Disk (GOLD), and Constellation Observing System for Meteorology Ionosphere and Climate 2 (COSMIC-2). However, progress in understanding I-T responses to external energy input at high latitudes is very limited.

For determining how the state of the ionosphere affects M-I coupling, ionospheric conductivity is a crucial physical parameter affected by solar radiation, precipitating particles from the solar wind and magnetosphere, and the neutral populations in the thermosphere. To calculate the conductivity, altitude profiles of multiple quantities—including plasma density and temperature and neutral density and composition—using a diverse set of instruments, are required. The neutral parameters are often obtained from empirical models, such as Mass Spectrometer Incoherent Scatter (MSIS). Currently, there are no measurements of the global distribution of conductivity required to understand how this critical parameter affects M-I coupling. Moreover, how the conductivity affects the magnetospheric dynamics is usually probed through numerical simulations owing to a dearth of in situ satellite observations in the magnetosphere.

Much progress on FACs has been achieved in the past decade, mainly owing to AMPERE and the Swarm mission. Utilizing the magnetometer onboard the Iridium satellite constellation, AMPERE provides continuous observations of global-scale FACs in both hemispheres, which enables numerous studies on the structure and intensity of the global FACs and how they respond to varying solar wind driving conditions. The AMPERE FACs are also used as high-latitude drivers for global I-T models. On the other hand, the Swarm mission provides high-sensitivity FAC measurements, including FAC filaments, through a single- or dual-satellite approach. Studies using Swarm have improved the understanding of small-scale FAC dynamics. However, what is missing is the ability to measure small-scale FACs over regional or continental scales. This is often needed to characterize the electrodynamic coupling within critical auroral forms, such as auroral streamers and the westward traveling surge, and convection features, such as cusp and Harang reversal. Drivers of FACs in the magnetosphere require multiple satellite constellations to calculate gradients of plasma pressure and flux tube volume. Unfortunately, there have been no dedicated missions targeting these important measurements.

Common auroral forms and airglow in the high-latitude regions—for example, auroral arcs, the westward traveling surge, Omega bands, and STEVE emission—are regions of intense coupling between the ionosphere and solar wind/magnetosphere. Energetic particles from the magnetosphere precipitate into the ionosphere and lead to enhanced ionization, conductivity, and spectacular optical emissions. Some of these emissions, such as STEVE, are associated with fast (up to 5 km/s) plasma jets in the ionosphere. These auroral forms and their evolution have long been used as a remote sensing tool to probe magnetotail dynamics. However, to fully decode the information transferred through them, their magnetospheric drivers need to be understood first. The limited number of in situ satellites in the magnetosphere and uncertainties of mapping between the ionosphere and magnetosphere have hindered progress in this area.

Theory, Modeling, and Simulations

Numerical modeling and simulations play an essential role in addressing M-I coupling. In the past decade, a coupled global I-T model was coupled with a global MHD model to self-consistently simulate the I-T response to energy input from the solar wind and magnetosphere and its role in regulating geospace dynamics. Significant progress has been achieved to characterize and quantify the I-T responses during geomagnetic disturbances.

Although coupled magnetosphere–ionosphere–thermosphere (M-I-T) models are now available, further developments are needed to address several science objectives. For example, neutral winds are a crucial parameter needed to determine heating rates and overall energy deposition rates for objective a. The neutral winds must be incorporated in global coupled simulations and validated against observations.

The altitude-dependent and energy-dependent particle precipitation into the ionosphere must be accounted for in coupled models. Moreover, the self-consistent coupling between the ionosphere and magnetosphere should account for induction and realistically treat electrodynamic coupling at a range of latitudes, moving away from the primarily high-latitude, electrostatic coupling that is typically assumed in global coupled models. Progress has been made in the past 10 years in several of these areas as more models incorporate advancements such as more realistic treatments of energy-dependent particle precipitation. However, more work is needed to (1) more widely incorporate a height-resolved ionosphere that includes inductive effects for transient phenomena, (2) develop more realistic treatments of particle precipitation that incorporate information from improved empirical models and/or physics-based approaches, and (3) develop models that can treat electrodynamic coupling processes that occur at high-, middle-, and low-latitudes, seamlessly coupling these regions to give global current continuity and plasma circulation.

To model FAC systems, self-consistently coupled M-I models must incorporate both north-south and east–west asymmetries. In the past 10 years, several models have explored the consequences of a range of asymmetries to multiscale FACs, including asymmetric currents arising from inclined interplanetary shocks and magnetotail dynamics. Future models need to more routinely include the capability of exploring the M-I-T coupling consequences of asymmetries such as inclined shocks, asymmetric reconnection, transient pressure disturbances from the ion foreshock and magnetosheath, ionospheric conductance, and the nondipolar components and offset axis of Earth's magnetic field.

Addressing the drivers of auroral forms requires several of the modeling advances listed above. Most importantly, realistic treatments of particle precipitation need to be included in self-consistently coupled M-I-T models.

How Does the Current Research Activity Motivate the Goal?

Current modeling and observational capabilities have yielded important insights into global electrodynamic coupling processes. Although often uncoordinated, combinations of satellite measurements and multinetwork ground-based measurements during fortuitous conjunctions have shown that mesoscale processes can play important roles in mass, energy, and momentum transfer. These have shown the need to routinely sample mesoscale structures in both the magnetosphere and ionosphere and obtain global distributions of critical parameters, such as ionospheric conductance and neutral winds, to quantify their role in the overall mass, energy, and momentum transfer between the magnetosphere and ionosphere. They have also shown that a wider range of observations are needed at mid-latitudes and low-latitudes to quantify electrodynamic coupling processes that occur during geomagnetic storms, along with models that can seamlessly capture all the unique processes that occur at high-, mid-, and low-latitudes.

Similarly, observations and models have both shown over the past decade that spatial variations, including north–south and east–west asymmetries and altitude-dependent dynamics in the ionosphere, can substantially alter global electrodynamic processes important to the understanding of the dynamics of the magnetospheric system. Thus, more global coverage from a combination of satellites and ground-based instruments is needed to improve mapping between the magnetosphere and ionosphere, along with modeling capabilities that can account for an altitude-resolved ionosphere.

C.2.4 Priority Science Goal 4: What Are the 3D Global Properties of Turbulence, Magnetic Reconnection, and Shocks, and What Is Their Role in Coupling Energy in the Magnetosphere?

While major breakthroughs have occurred in the past decade on the microphysics governing reconnection, turbulence, and shocks, major gaps have remained in the 3D meso-/global-scale properties of these processes. Similarly, the interplay between these larger scales and microscales is largely unexplored. This motivates PSG 4 for the coming decade. Table C-6 lists the objectives needed to answer this question.

TABLE C-6 Objectives for Priority Science Goal 4

Priority Science Goal (4 of 4)	Objectives
What are the 3D global properties of turbulence, magnetic reconnection, and shocks, and what is their role in coupling energy in the magnetosphere?	**4.a.** Determine how the magnetic reconnection region forms and evolves on both the dayside and the nightside. **4.b.** Determine the nature of and interplay among turbulence, magnetic reconnection, and shock dynamics. **4.c.** Determine how energy is partitioned and converted at the bow shock. **4.d.** Determine the feedback between the physics at macroscales and microscales in turbulence, magnetic reconnection, and shocks.

The past decade saw an explosion of progress on the microscale physics of magnetic reconnection owing to the new MMS observations. While the electron diffusion region has been found and studied extensively, how magnetic reconnection onset occurs and how reconnection evolves at the magnetopause and in the nightside plasma sheet are still unsolved questions. What is still largely unknown are the mesoscale properties of magnetic reconnection and their feedback on global properties of the magnetosphere.

Earth's bow shock preprocesses plasma before it directly interacts with Earth's magnetosphere, compressing and heating it to form the magnetosheath. The region both in front of the bow shock (the foreshock) and behind the bow shock (the magnetosheath) are often turbulent, and this turbulence likely plays an important role in the fate of plasma as it crosses the shock. In the past decade, MMS was able to probe the small scales on the Earthward side of the shock with unprecedented resolution. However, as with reconnection, a global characterization of the bow shock and the resulting turbulence is missing.

The conversion of solar wind kinetic energy into heating and compression of the plasma strongly affects the geospace response and may contribute to negative space weather consequences. But, exactly how this conversion occurs, and the ultimate distribution of the energy is a major unsolved question.

It is understood that macroscale configuration changes trigger microscale processes, and that in turn the microscale processes impact the global dynamics. But the interaction and feedback between the scales is still not well understood.

Additional insight into the broad understanding of these fundamental processes can also be obtained by supporting comparative studies that leverage observations of these phenomena in Earth's magnetosphere as well as those from elsewhere in the heliosphere (e.g., reconnection in the corona, turbulence in the solar wind, energy conversion at the termination shock).

Current Research Activity

Link to Current Missions

MMS has provided unprecedented views of the kinetic scales of reconnection regions as discussed in Section C.1. While direct measurements of kinetic dissipation are now possible, their impact on the dissipation and energy exchange at mesoscales and global scales are largely unexplored. MMS will maintain its electron-scale separation through calendar year 2023, but in subsequent years it will add time periods with larger separations in order to investigate cross-scale physics, including electron- to ion-scale time periods, and ion to MHD scale separations. Thus, MMS can be used to start to address the objectives of this goal. In addition, conjunctions between spacecraft from existing missions are being used to address this goal for limited time periods.

Conjunctions with probes from multiple space-based missions such as THEMIS and Cluster have provided measurements along the dayside magnetopause demonstrating that reconnection can be widespread, extending over many Earth radii, or limited in spatial extent, potentially active over less than a single Earth radius in one or a series of coexisting patches. Although some progress has been made at the necessary mesoscale and MHD scales to constrain numerical models, experimental results are lacking to test model predictions and are needed to enable progress in understanding.

Linking spatially localized patches of reconnection with longer extended reconnecting regions, time-dependent growth or spreading of reconnection remains an important area of research. Several pioneering studies have been conducted over the past decade using solar imaging from Solar Dynamics Observatory (SDO) as well as THEMIS in situ observations and ground-based radar to constrain models of reconnection spreading; however, possible experimental work in this area is limited owing to the meso- and macro-spatial scales of the problem and the limitations of current observing platforms. Temporally, micro-scale in situ observations of reconnection have reported an oscillating process while the connection to the macroscale properties or how the large-scale boundary conditions may drive temporal behavior remain unknown.

Although reconnection, turbulence, and shocks have been studied independently for decades, MMS has provided an initial assessment of their connections to each other. The dayside magnetosphere is an excellent laboratory for this interplay because of the interaction between Earth's bow shock, the often turbulent magnetosheath, and the resultant reconnection. The larger scales measurements available from MMS in the next few years will provide new observations to help understand the interactions.

Using MMS to determine downstream energy fluxes and Wind to establish upstream conditions, individual case studies of the bow shock have been able to determine the partition of energy release between enthalpy flux, energetic particles, or some other form. The energy conversion mechanisms have been directly measured, including such mechanisms as a cross-shock electrostatic potential, current-driven instabilities (e.g., the Buneman and electron-cyclotron drift instabilities), electron-only magnetic reconnection in the shock transition region, other WPIs, and particle acceleration and reflection. But a focused mission with regular multipoint measurements on both sides of the shock would be necessary to resolve how energy is partitioned.

Looking forward, the NASA Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS) mission is under development and will provide valuable measurements in this research area. The mission is scheduled to launch in 2024 and will be composed of two low-altitude, highly inclined spacecraft that will pass through the magnetospheric cusp. The two spacecraft will have the same orbit with the second spacecraft following the first by 10–120 s to probe how cusp ion dispersions evolve temporally. Cusp ion dispersions map to the reconnecting dayside magnetopause and with these measurements TRACERS will seek to (1) determine whether magnetopause reconnection is primarily spatially or temporally variable for a range of solar wind conditions, (2) determine how the reconnection rate evolves during temporally varying reconnection, and (3) determine to what extent dynamics structures in the cusp are associated with temporal versus spatial reconnection. These objectives are anticipated to lead to major progress and are well in-line with the driving science goals of the community for the next decade.

The HelioSwarm mission is a NASA MIDEX constellation that will capture the first multiscale in situ measurements of the solar wind. The primary science goals are (1) reveal the 3D spatial structure and dynamics of turbulence in a weakly collisional plasma, and (2) ascertain the mutual impact of turbulence near boundaries and large-scale structures. HelioSwarm is scheduled to launch in 2028 and consists of one hub spacecraft and eight co-orbiting small satellites called "nodes" that range in distance from each other and the hub spacecraft.

Ground-Based Facilities

Ground-based facilities are also used to study this area. The SuperDARN radars are used to study maps of ionospheric convection. When radar coverage and radar scatter is appropriate, these maps can cover large spatial regions (i.e., many hours in local time) at high latitudes where ionospheric field lines can map to the dayside magnetopause. Researchers have made major progress over the past decade using these tools to study the flow over the open-closed boundary that maps to reconnecting field lines along the magnetopause. At times the flow has been temporally steady and extended in local time as well as occurring in bursts or spatially localized local time regions, implying magnetic reconnection and subsequent convection can occur through a number of different modes at Earth's dayside magnetopause. Substructure in the magnetospheric cusps is probed through the EISCAT and more recently the EISCAT3D radars in northern Europe. The density profiles and cusp substructures have revealed valuable information on particle precipitation and periodicity of magnetopause reconnection for different modes of solar wind driving.

Global and system-level solar wind-magnetosphere coupling has been probed using Polar Cap Indices (PCI), which are based on ground-based magnetometers. The PCI are commonly used for probing the role of solar wind features, such as density or Mach number, on the driving of the magnetosphere. Over the past decade, these have been used to further the knowledge of polar cap saturation and the potential role of features such as cold magnetospheric plasma, magnetosheath flow patterns, or uncertainty in solar wind measurements. Ground-based magnetometer arrays have also been used to advance the understanding of how the magnetosphere responds to temporally periodic features along the magnetopause such as Kelvin-Helmholtz waves or transient features impacting the boundary such as magnetosheath high-speed jets that can generate enhanced flow or traveling convection vortices that propagate tailward within the ionosphere over the polar cap.

Laboratory Experiments

Laboratory experiments complement these space- and ground-based observations of basic plasma phenomena. The advantage of laboratory experiments is that the system configuration can be controlled and tuned, and it is much more straightforward to determine the global magnetic topology of the system. On the other hand, these experiments often do not have the disparate separation of scales between global and micro found in the heliosphere. For example, the ratio of global to kinetic length scales in the magnetosphere is typically on the order of a thousand, while for many laboratory experiments it is a few tens. The PHAse Space MApping (PHASMA) device at West Virginia University has achieved the first laboratory measurement of electron distribution functions and studied how the plasma is heated during electron-only reconnection. The Magnetic Reconnection eXperiment (MRX) at Princeton Plasma Physics Laboratory has been used to study a wide range of problems recently, including plasma heating, anomalous resistivity, 3D effects, and reconnection rates. The Terrestrial Reconnection EXperiment (TREX) at the University of Wisconsin can strongly drive reconnection, leading to a shock magnetic flux pileup that accelerates the reconnection rate. The Swarthmore Spheromak Experiment (SSX) examines the merging of spheromaks and was able to directly measure the diverging flows associated with reconnection. The much larger, multi-institutional Facility for Laboratory Reconnection Experiments (FLARE) laboratory experiment is coming online presently. On a completely different front, reconnection in the high energy density regime has been measured using laser facilities such as OMEGA at Rochester or the National Ignition Facility (NIF) at Livermore National Laboratory.

Shocks in plasmas have been studied extensively at laser facilities (e.g., OMEGA and NIF). Pulsed power generators, such as Mega Ampere Generator for Plasma Implosion Experiments (MAGPIE) at Imperial College, have also been used, and a laser-driven magnetic piston has been implemented at the Large Plasma Device (LAPD) at the University of California, Los Angeles. Last, turbulence in the laboratory is being studied with plasma wind tunnels such as at LAPD, the SSX at Swarthmore, and at the Bryn Mawr Plasma Laboratory.

Theory and Modeling

For probing the kinetic physics critical to the study of shocks, turbulence, and reconnection, only fully kinetic models (e.g., Vector PIC [VPIC] and Electromagnetic PIC Code [P3D]) include all of the relevant physics. The difficulty of course with including all physics is that reaching even mesoscales in 3D requires extremely computationally time intensive experiments, only a handful of which can be run each year. On the other hand, 2D and smaller 3D simulations have yielded a wealth of information that has been cross compared with satellite observations and laboratory experiments. Two-fluid and PIC models exploring 3D effects have found that spatially localized reconnection is a natural product of reconnection physics on the mesoscale. The localized reconnection prevents sufficient current sheet thinning to enable widespread reconnection on meso- and macro-scales. Similar localized structure has been observed in global kinetic-hybrid models, such as Vlasiator, where dayside reconnection has manifested as spatially localized patches, even during steady driving solar wind conditions. Theory and both fluid and kinetic modeling efforts have produced a number of physical models to predict how quickly, in which direction, and with what driving physics reconnection may spread.

At the other extreme, global magnetospheric MHD simulations and associated computational frameworks (e.g., MAGE, Open Geospace General Circulation Model [OpenGGCM], and Space Weather Modeling Framework [SWMF]) allow a truly global picture of the magnetosphere system and nearby solar wind, can include self-consistent ionospheric convection models, and can simulate long periods in the magnetosphere at relatively low computational cost. However, the small-scale dissipation and reconnection physics is ad hoc. There are numerous avenues of research seeking to allow global models while at the same time model global spatial and temporal scales. Hybrid simulations (e.g., P3D-Hybrid) include ion kinetic physics but treat the electrons as a fluid, eliminating both electron kinetic scales from the simulation as well as plasma waves and lightwaves. Global hybrid simulations (e.g., ANGIE3D, HYbrid Particle Event-Resolved Simulator [HYPERS], and Vlasiator) in the past decade have become attainable, especially in 2D or with artificially larger kinetic scales. Another avenue is to embed kinetic PIC simulations inside of global MHD simulations (e.g., MHD with Adaptively Embedded PIC [MHD-AEPIC]). Determining how to allow the two-way flow of information at the boundaries between the two simulations is an area of ongoing research.

How Does the Current Research Activity Motivate the Goal?

As mentioned previously, in the past decade MMS has opened an unprecedented era of high-resolution observations in near-Earth space, leading to major progress in understanding the microphysics governing shocks, magnetic reconnection, and turbulence. However, the meso-scale evolution, interplay between the different processes and impacts of this kinetic physics is missing.

The current research activity highlights the need for a mission or missions that will establish the behavior for these fundamental processes over a full range of scales. Such a mission is critical for developing the system-level science necessary for predictive models of near-Earth space.

C.2.5 Role of Research and Analysis Development Grant Programs for the Priority Science Goals

While the focus is often on the role that missions and ground-based facilities play in moving science forward, much of the scientific output is funded by smaller grants from NASA, NSF, the Air Force Research Laboratory, and the Department of Energy (DOE). The general programs play a very important role in enabling investigations over the full range of topics, allowing innovative, high-risk ideas to be pursued. The more focused programs have also played a very important role. For example, the NSF Geospace Environment Modeling (GEM) program, particularly with its annual GEM workshops, has fostered community discussions that motivate the PSGs stated here. Specific examples of connections to recent focus groups include: "Magnetotail Dipolarizations and Its Effects on the Inner Magnetosphere" (PSG 1), "The Impact of the Cold Plasma in Magnetospheric Physics" (PSG 2), "Interhemispheric Approaches to Understanding M-I Coupling" (PSG 3), and "Magnetic Reconnection in the Age of the Heliophysics System Observatory" (PSG 4). A new focus group, "Comparative Planetary Magnetospheric Processes" also supports the panel's longer-range science goal.

Similarly, the LWS Targeted Research and Technology (TR&T) Program has encouraged in-depth studies of topics that have informed the PSGs. Recent topics have included "Coupling of the Solar Wind Plasma and Energy to the Geospace System" (PSG 1), "Ion Circulation and Effects on the Magnetosphere and Magnetosphere–Ionosphere Coupling" and "Pathways of Cold Plasma Through the Magnetosphere" (PSG 2), "Causes and Consequences of Hemispherical Asymmetries in the M-I-T system" (PSG 3), and "Fast Reconnection Onset" (PSG 4). The most recent call for the topic, "Synergistic View of the Global Magnetosphere," supports the overall objective to obtain a system science view of the magnetosphere.

Last, one of the science themes for the Center for Geospace Storms (CGS)—one of the first NASA Diversify, Realize, Integrate, Venture, Educate (DRIVE) Science Centers—is improving modeling of the mesoscale dynamics of the plasma sheet and its connection to the inner magnetosphere, a topic at the heart of PSG 1.

One unique challenge in addressing PSG 3 relates to the emphasis of some programs on projects that primarily involve satellite data analysis efforts with little or no support for combined efforts involving both space- and ground-based data. Recent modifications to programs (e.g., NASA Heliophysics Supporting Research [HSR]) to allow for more substantial ground-based data analysis efforts address this challenge. Another challenge is that there are limited opportunities for proposing data analysis on open topics using missions that are no longer operating. While HSR does permit analysis of data from all spacecraft, proposers are encouraged to include a substantial amount of theoretical work.

Instrument technology development through the NASA Heliophysics Technology and Instrument Development for Science (H-TIDeS) program is critical for the instrumentation needed to achieve the panel's science priorities. Examples include development of instrumentation to measure the lowest energy ions and electrons, improved neutral imaging to enable higher temporal and spatial resolution global measurements of magnetosphere particles, soft X-ray instruments designed to monitor global charge-exchange processes, and EUV instruments tailored to novel wavelengths to observe different species.

Last, the Heliophysics Low-Cost Access to Space (H-LCAS) and Heliophysics Flight Opportunities in Research and Technology (H-FORT) programs play a number of critical roles. Sounding rockets can get high-resolution data in regions inaccessible to spacecraft, and so often perform cutting-edge science, particularly in the area of M-I coupling. These lower-cost opportunities allow testing of newly developed instrumentation to increase technical readiness and they provide opportunities for students to get hands-on experience in developing space hardware, experiencing integration and testing as well as mission operations, and the subsequent data analysis.

C.3 LONGER-RANGE GOAL: HOW DO OTHER PLANETS' MAGNETOSPHERIC CHARACTERISTICS AND CONFIGURATIONS AFFECT THEIR MAGNETOSPHERIC PROCESSES, INTERACTIONS, AND DYNAMICS?

While the previous four goals have focused on Earth's magnetosphere, the processes studied apply to magnetospheres at all planets. As discussed in Cohen et al. (2023), one of the best ways to learn about Earth and where it resides on the planetary spectrum is to study the diversity of magnetospheric and atmospheric systems and processes that exist on neighboring worlds. The planetary systems within the solar system provide data points that can provide deep insight into the fundamental physics that governs the local heliophysics environment.

The space environments of the worlds in the solar system also provide natural laboratories to study processes that occur throughout the universe. Throughout the solar system, researchers can combine the ground truth of in situ particle measurements with simultaneous remote measurements equivalent to what is done for extrasolar objects. So much more can be learned about the fundamental physical processes in the universe by adding in situ measurements from additional data points to those of Earth, specifically those that may be more analogous to other astrophysical systems (i.e., with relativistic particle acceleration, very strong and rapidly rotating magnetic fields, synchrotron electromagnetic emissions, natural X-ray sources).

To date obtaining sufficient measurements across multiple magnetospheres of the solar system has been difficult owing to the sparse, sometimes decades-long gaps between magnetospheric missions beyond Earth and the resource limitations that usually accompany them. Although most systems (with the exception of Uranus and Neptune) have been explored more than once, those missions are still largely limited to specific local times, radial distances, inclinations, and/or measurement capabilities. As expected, no magnetosphere has been explored as comprehensively as Earth's. Entire regions, energy and frequency regimes, emission bands, populations, and seasons remain unexplored at the other magnetospheres in the solar system.

The objectives necessary to answer this question are given in Table C-7.

The diverse worlds within the solar system provide crucial environmental conditions that are not replicated at Earth but can provide deep insight into fundamental space plasma physics processes. The parameter space covered by these systems not only provides insights into processes that cannot be observed at Earth but can also be used to understand Earth's magnetosphere, both today and in the past. Earth's magnetosphere is often used as a template from which to understand other planetary environments. However, as understanding of other magnetospheres in

TABLE C-7 Objectives for the Longer-Range Goal

Longer-Range Goal	Objectives
How do other planets' magnetospheric characteristics and configurations affect their magnetospheric processes, interactions and dynamics?	**LR.a.** Determine which processes are common to all planetary magnetospheres. **LR.b.** Determine how variations in planetary systems give rise to specific magnetospheric characteristics. **LR.c.** Determine scaling laws for fundamental magnetospheric processes that can be extrapolated for application to exoplanetary systems.

the solar system has grown, researchers have begun to reassess how common Earth's magnetosphere may truly be. Exploring and understanding the characteristics and dynamics of other planetary magnetospheres can help to better understand how Earth's magnetosphere compares to the range of magnetospheric possibilities.

As discussed in Cohen et al. (2003):

> [The terrestrial magnetosphere] is often used as the archetype for a solar wind-driven system in contrast to that of Jupiter, which is largely believed to be driven by internal mechanisms. However, Mercury boasts the unique combination of a weak internal magnetic field and close proximity to the Sun, producing an Earth-like magnetosphere which is possibly the most solar-wind-driven in the heliosphere. Venus's interaction with the solar wind-sourced interplanetary magnetic field drives currents within its ionosphere and potentially metallic core, which create an induced magnetosphere including an extended magnetotail. Mars's interaction with the solar wind largely occurs via currents that link to the ionosphere; its small, incredibly strong localized patches of surface magnetization in its crust create areas where local magnetic fields block the access of the solar wind to the ionosphere. The complexity of interactions with the solar wind that exist within our own solar system [need to] be leveraged to increase the understanding of our own planet and of the fundamental interactions that are shared between planets. Other objects such as asteroids and comets, can also be responsible for large magnetospheres in the solar system.

The terrestrial aurora remains a major focus of study of M-I coupling, with decades of observations of the global field-aligned current system and auroral precipitation. However, despite having only regional "mini magnetospheres," multiple distinct auroral processes—including diffuse, discrete, and proton aurora—are still found at Mars. Cohen et al. (2023) also discussed that Neptune's magnetospheric configuration generates a unique configuration where the plasma sheet becomes cylindrical; a major mystery persists as to how such a complex current sheet would close. As with many things, Jupiter has the most intense auroral emission in the solar system, which seems to be largely decoupled from solar wind interactions and is instead dominated by internal processes. However, new results suggest that extreme auroral energies at Jupiter may provide a seed mechanism for the acceleration of the energetic particles in its radiation belts.

Overall, the magnetospheres beyond Earth's remain largely unexplored. Even Mars, Jupiter, and Saturn, which have been surveyed the most, have only been investigated using disjointed missions targeting different science aspects with different instrumentation over several decades. As such, understanding global system dynamics is incredibly difficult compared to Earth where a majority of the HSO operates missions spanning from sounding rockets and to large-scale multispacecraft missions in coordination with ground-based assets.

C.3.1 Current Research Activity

Operating and Past Missions

In addition to the myriad of geospace missions in the HSO that have been discussed in addressing the previous science goals, a wide array of in situ missions and ground-based and orbital remote sensing assets have also addressed the longer-range goal of comparative magnetospheric studies. Mercury has been explored by the Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission, which ended in 2015, and will be further investigated by the joint ESA-JAXA BepiColombo mission expected to insert into the system in 2025. The induced Venusian magnetosphere was studied by the Venus Express mission, which ended in 2014, as well as flybys by both the Parker Solar Probe and Solar Orbiter missions. The understanding of Mars's bow shock, localized "mini magnetospheres," and ion outflow have come from the ongoing MAVEN mission. Additional investigations of the solar wind-magnetosphere interaction at Mars is expected from the upcoming Heliophysics Division-funded ESCAPADE mission. New insights into the Jovian polar regions have come from the ongoing Juno mission with novel multipoint investigations expected to come from ESA's Jupiter Icy Moons Explorer (JUICE) and NASA's Europa Clipper missions that are anticipated to arrive in the system in the 2030s. A much more comprehensive understanding of the Saturnian magnetosphere resulted from the Cassini mission, which concluded in 2017. Remote sensing of the upper atmospheres, aurorae, kilometric radiation, and synchrotron radiation of the giant planets has also come from ground-based (e.g., Low Frequency Array [LOFAR], Very Large Array, Atacama Large Millimeter/submillimeter Array [ALMA], and Arecibo) and space-based (e.g., Hubble Space Telescope, Hisaki, and James Webb Space Telescope [JWST]) assets at Earth.

Research and Analysis and Development Grant Programs

Comparative planetary magnetosphere studies are supported by several rather focused opportunities across funding agencies. At NASA, the most explicit opportunities for broad comparative studies are the Heliophysics Division's LWS Program—where a strategic science area focuses on topics such as atmospheric depletion and stripping and magnetospheric shielding that readily support investigation of varying magnetospheric configurations and characteristics and the Planetary Science Division's Solar System Workings Program—which tends to accept a very wide scope of planetary science investigations. While several mission-limited programs in both the Heliophysics and Planetary Science Divisions could potentially support comparative studies, these investigations must be focused primarily on the missions prescribed in each opportunity; these include the Heliophysics Guest Investigator Open (HGIO), HSR, Discovery Data Analysis, New Frontiers Data Analysis, Cassini Data Analysis, and Mars Data Analysis programs. Recently, several NSF programs—notably the Magnetosphere Research and GEM—have specifically welcomed studies focusing on comparative magnetospheric studies.

Theory, Modeling, and Simulations

As previously discussed, the past decade has seen a significant advance in the development of new magnetospheric models as well as the adaptation and application of high-fidelity models developed for geospace studies to other planetary systems. At Mercury, recent studies have investigated the induction effect of the planetary conducting core on the global magnetospheric interaction and the magnetopause dynamics under various solar wind driving conditions. Similar studies also explored the effects of solar wind driving conditions on the locations and characteristics of the bow shocks and the induced and localized magnetospheres of Venus and Mars. Multiple models have also found surprising similarities in the levels of ion outflow and atmospheric escape across Venus, Earth, and Mars despite their very different magnetospheres. Advanced high-resolution MHD simulations of Jupiter explore the interactions of the planet's rapidly rotating magnetic field with the planet's upper atmosphere, the solar wind and IMF, including generation of boundary instabilities, the Io plasma torus, and the magnetic field of Ganymede. Similar studies at Saturn found that the magnetopause location is insensitive to the orientation of the IMF and leveraged kinetic simulations to explore the access of energetic particles to the exobase of its largest moon, Titan. Although still somewhat crude compared to those of other planets owing to the lack of in situ observations to constrain them, new MHD simulations were developed in the past decade to explore the seasonal and diurnal variability of the highly dynamic and complex magnetospheres of Uranus and Neptune. Unfortunately, to-date studies are missing that implement a framework to simulate outer planetary radiation belt populations by tracing test particles through underlying MHD simulations, as has been performed for Earth.

C.3.2 How Does the Current Research Activity Motivate the Goal?

The limited research of planetary magnetospheres and M-I coupling beyond Earth has traditionally been conducted by missions and research programs led by the NASA Planetary Science Division. Historically, these collaborations between the Heliophysics and Planetary Science Divisions have been very successful. However, the science priorities of the planetary science community have narrowed over the past decade toward planetary origins, processes, and habitability. This is showcased by the fact that the latest planetary science and astrobiology decadal survey, *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (NASEM 2023) only list magnetospheres as a part of 1 of its 12 priority science question topics. Unlike most planetary missions, those funded by the Heliophysics Division at Earth are usually instrumented with payloads that comprehensively explore the particle and field populations necessary for most magnetospheric studies.

In situ particle and field instrumentation is becoming less frequent on planetary science missions. For example, the high-energy particle instrument was descoped from the Europa Clipper payload early in its formulation. The planned plasma measurements will be coarse and are only meant as a tool to support characterizing the magnetic induction from Europa's subsurface ocean. Likewise, the recent Uranus Orbiter and Probe concept—the highest-priority, new large-scale mission in *Origins, Worlds, and Life*—allocates only 14.5 kg and 13.1 W (~20 percent) for the in situ fields and particle instruments (compared to >100 kg [>33 percent] for the in situ instruments on Cassini). Furthermore, neither of the Discovery missions selected for Venus (i.e., Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy [VERITAS] and Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging [DAVINCI]+) will carry any instruments of significance for space physics research, as has been the case for the majority of the most recent Discovery missions. The Earth system also benefits from persistent upstream solar wind monitoring from the Sun–Earth L1 point that enables advanced knowledge of the solar wind driving of the system.

Over the past decade there has been growing interest in the solar and space physics community in comparative magnetospheric studies. As previously discussed, a number of research programs in the NASA Heliophysics Division and the NSF Geospace Section have solicited and supported comparative planetary magnetosphere studies. NASA Heliophysics has also increased its support of missions to other planets by funding the upcoming ESCAPADE mission, assuming operations of the Radiation Assessment Detector (RAD) on the Mars Curiosity rover and coordinating cruise science operations for future outer solar system missions such as JUICE and Europa Clipper. Community interest in these comparative magnetospheric studies is also represented by cross-disciplinary efforts such as the Whole Heliosphere and Planetary Interactions initiative and the Comparative Planetary Magnetospheric Processes Focus Group under way as part of the NSF GEM program. As has been the case for several decades, the space physics community also took advantage of serendipitous opportunities for collaborations with the Planetary Science Division, largely stemming from long cruise durations (e.g., Juno, BepiColombo, JUICE, and Europa Clipper), unique access to regions of the outer solar system (e.g., New Horizons), and gravity assists (e.g., Parker Solar Probe). However, except for the upcoming ESCAPADE mission, the NASA Heliophysics Division has yet to select and fly a mission targeting a planetary system besides Earth.

Despite this growing interest, a comprehensive understanding of comparative planetary magnetospheres will require a long-term approach. First, interplanetary cruises to other planets— especially those in the outer solar system—take years, if not decades. As such, even missions implemented today would take a much longer time (relative to typical Earth missions) to return their initial science results. Furthermore, because there are so many magnetospheres in the solar system to study and compare, simply exploring them all will take significant time and investment by the community. Several examples exist for how this could be implemented. The first example would be a direct hardware contribution by the Heliophysics Division to future Planetary Science Division missions. However, this approach would be the most intrusive on the primary mission's scope and requirements; it is also unclear how this would be implemented for PI-led (e.g., Discovery or New Frontiers) mission. A second example would be for NASA Heliophysics to solicit, select, and fund "cross-disciplinary scientists" to join the primary Planetary Science mission science team to define objectives and coordinate the necessary observations to address compelling heliophysics science. The final option would be for NASA Heliophysics to fund the instrument teams on Planetary Science missions to obtain, calibrate, and archive additional heliophysics-relevant data that is outside the scope of the primary mission, as has been considered for Europa Clipper.

C.4 EMERGING OPPORTUNITIES

Sections C.2 and C.3 have focused on specific PSGs to address over the next decade. In addition, the panel has identified a number of impactful developments that have recently emerged that are expected to contribute significantly to the broader understanding of magnetospheric processes over the next 10 years. The first two are new topics where magnetospheric expertise can contribute to new discoveries. The next four are new technological advancements that will enable advancement of discoveries in magnetospheric physics.

C.4.1 Leverage the Capability to Detect Exoplanet Magnetospheres to Enable Comparative Studies with Known Solar System Magnetosphere

Although the direct remote detection of auroral emissions from exoplanets (i.e., planets orbiting stars other than the Sun) has yet to be confirmed, emissions from larger objects such as ultracool dwarfs can provide estimations of their magnetic fields and insight into the presence of electrons in the MeV range. As observing capabilities rapidly advance, the direct detection of exoplanetary kilometric radiation with ground-based telescopes may not be far off and the search for exo-magnetospheres has become an exciting topic. Looking ahead, the community will be presented with new opportunities to meaningfully interpret these anticipated future observations. First, it will be necessary to acquire in situ measurements of auroral radio emissions within the solar system to understand these local sources and therefore build up the reference frame from which to interpret distant radio emissions from magnetospheres that will never be explored via in situ spacecraft. Second, it will be critical to expand theory and modeling efforts to investigate the diversity of magnetospheric characteristics and stellar-magnetosphere interactions that may exist beyond the solar system.

C.4.2 Leverage the Growing Field of Astrobiology to Address the Question of Whether a Magnetic Field Affects Habitability

Earth constitutes a uniquely habitable planetary body with a present atmospheric composition quite different from both that of other planets in the solar system and that which existed on Earth billions of years ago. Variations in atmospheric oxygen levels and geomagnetic field intensity may influence the habitable environment on Earth; therefore, understanding the evolution of the atmosphere over geological times can provide insights into the history of the planet. It can also allow researchers to identify the circumstances under which habitable conditions similar to those on Earth can exist elsewhere.

Several key factors control atmospheric evolution, including particle influx from space (e.g., meteors), biospheric reactions, subsurface activities (e.g., volcanic, bacterial denitrification), and a net particle escape of atmospheric constituents into space. Owing to the size of Earth's magnetosphere, there is no direct interaction between the solar wind and the neutral atmosphere, an interaction that can play a crucial role in escape at nonmagnetized planets like Mars. In addition, the thermal escape of neutrals from Earth is limited to only the lightest elements, like hydrogen and helium. However, heavier elements can escape into interplanetary space as ions after gaining sufficient energy to overcome the gravitational force. This escape pathway is facilitated by the chemical and electrodynamics processes operating in the terrestrial ionosphere, allowing atmospheric migration and escape to occur without requiring direct interaction with solar wind particles or high thermal speeds.

Furthermore, magnetic fields of rocky planets are thought to play an essential role in planetary habitability, as they may regulate the interaction between a planet and the stellar wind, hence the global distribution of energy dissipated into the planetary atmosphere by the stellar wind. Conversely, the absence of an intrinsic magnetic field may make a planet more prone to atmospheric ablation because it allows for direct interaction between the stellar wind and the neutral atmosphere. However, the extent to which a planetary magnetosphere prevents or controls the loss of its atmosphere owing to stellar wind erosion depends primarily on how well it prevents energy and momentum transfer into the atmosphere or inhibits the plasma escape. This is still largely unknown, and the role of planetary magnetic fields in facilitating habitable environments remains an open question of significance for studies of Earth's history, as well as those of Mars, other solar system planets, and exoplanets.

Comparative observations and modeling of atmospheric loss under different magnetic field configurations are needed to determine the impacts of magnetic fields on atmospheric evolution. This is a strongly interdisciplinary problem requiring the expertise of scientists who study Earth's magnetosphere and atmosphere, other solar system planets and exoplanets. Much of the detailed knowledge needed to extrapolate to other systems comes from extensive studies of plasma interactions and atmospheric loss at Earth. Cross-divisional studies are needed to better define the conditions required for habitability and to determine how to extend in situ knowledge from Earth to other solar system bodies and then to the vast number of exoplanets that are being discovered.

C.4.3 Leverage Large Commercial Constellations to Advance Magnetospheric System Science

The Need for Expanding Presently Available Multipoint Observations

The PSGs in Section C.2 emphasized the importance of system science for magnetospheric physics. Fully characterizing the vast, complex, highly dynamic magnetospheric environment requires simultaneous measurements at a large number of locations over long intervals so that the observations will encompass many representative levels of activity. The self-organization properties of plasmas are helpful in producing a coherent picture from the limited number of observations available. At the same time, using modern, low-resource sensor technologies to collect basic plasma and field measurements from as many locations as economically possible would vastly increase the knowledge of the system.

Multipoint data have several uses in the large, undersampled magnetosphere system:

- *Model development and validation:* Having extended coverage of magnetospheric regions is key in creating and improving models. Depending on the types of data available, several functions and higher-level products can be generated to provide constraints on model behavior.
- *Data assimilation:* Ingesting observations into models has shown promise for radiation belt and ionospheric environments. The community is developing data assimilation techniques for the magnetosphere as well as advanced techniques such as OSEs and OSSEs. In all of these the use of multipoint measurements is essential and leveraging commercial constellations can make a significant difference.
- *Data analysis:* Having extended coverage of magnetospheric regions is key in resolving questions regarding relevant scale sizes and long-term environment characterization, as well as providing context for event analysis. Having a historic record that is as continuous and as consistent as possible will be useful for statistical studies, space climate (solar cycle) studies, and event selection and comparison.

Emerging Observational and Technology Options

Several recent developments can significantly advance the required measurements for system science.

- *Commercial satellite constellations:* The advent of these constellations in the early part of the 21st century is an emerging opportunity for magnetospheric (and ionospheric) observations. Deployed predominantly at LEO, but in smaller numbers also in medium Earth orbit (MEO) and geostationary Earth orbit (GEO), these satellites can provide additional observational platforms for basic magnetospheric measurements. Successful scenarios include either collecting data via the satellites' commercial payload or by hosting dedicated scientific sensors. Mission goals can range from a technology demonstration for a novel sensor to a quasi-operational function. Data from constellations as diverse as Iridium Next, Spire, PlanetIQ, Starlink, and others have been used to improve models of the magnetospheric environment and the ionospheric boundary.
- *Low-resource, smart instruments:* Instruments of low size, weight, and power (SWaP) have become widely available. Standard payload components that can have a dual use, for satellite health status and science measurements, include dosimeters, charging monitors, magnetometers, accelerometers, GPS sensors, visible (VIS) and infrared (IR) complementary metal oxide semiconductor (CMOS) detectors, and others. Sensors combining silicon detectors with an electrostatic analyzer have been used to measure precipitating energetic electron and proton spectra at LEO. Low-SWaP fluxgate magnetometers have also been developed by several groups for precision measurements and many other applications. CMOS-based imaging components have steadily decreased in size and mass while maintaining high performance. Novel coatings have been developed for multispectral UV, VIS, and IR optical elements. Improving on legacy UV and VIS auroral sensors—such as those from NASA's Polar and TIMED missions and the Department of Defense's (DoD's) DMSP satellites—new designs for compact, wide-field, multispectral imagers for LEO have been developed.
- *Commercial spacecraft standardization:* Technology improvements are not limited to instruments. High-capacity SmallSat and CubeSat buses are becoming more standardized and interoperable. These buses can serve as platforms that collect basic plasma, particle, and field measurements to address the PSGs.

- *Increasing data accessibility:* In some cases, environmental data have been measured on government or commercial satellites but need to be made available to the research community to advance model development. The GPS particle data release is a case in point. In 2017–2018, several proton flux data sets from the GPS constellation's Combined X-ray Dosimeter (CXD) and Burst Detector Dosimeter (Block) IIR (BDD-IIR) sensors were released to the community. The release has enabled intercalibrations with sensors at GEO and LEO, increased radiation belt model accuracy, and an improved understanding of acceleration and loss processes in the heart of the outer belt.

Use Cases and Relation to Priority Science Goals

In a typical scenario, a commercial satellite system may provide in situ or remote sensing data such as the plasma density, particle flux, ambient magnetic field, and/or auroral and airglow imagery. Depending on the number and configuration of deployed sensors and the accuracy, range, and resolution of the resulting data, additional magnetospheric and ionospheric variables can be derived.

One such example is the NSF-funded AMPERE project, which has utilized commercial data to provide nearly continuous, global observations of a critical parameter of M-I coupling—FAC density at high latitudes—for over a decade. AMPERE data comprises global magnetic field measurements from the Iridium satellite constellation via the telemetry stream from the body-mounted avionics magnetometers and provides instantaneous observations of both hemispheres spanning all levels of geomagnetic activity, rather than requiring statistical analysis for local time coverage or multiple passes at different times that may not capture all of the temporal variation of FAC development. Along with revealing details of magnetospheric dynamics and solar wind-magnetosphere interactions through current closure in the polar cap region and impacts of high-latitude driving on the ionosphere–thermosphere–mesosphere (ITM) system, AMPERE has demonstrated utility for machine learning algorithms and data assimilation and shown promise for Earth main field studies and models.

Another project is the remote sensing of ionospheric electron density via radio occultation techniques implemented by commercial providers such as Spire and PlanetIQ. This is important for understanding characteristics and responses of the ionosphere as well as phenomena in the ITM environment, both of which have significant impacts on aspects of M-I coupling processes. Because of the significance of these measurements and implications for space weather, the National Oceanic and Atmospheric Administration (NOAA) has developed a commercial data buy project that includes these providers.

In a third use case, measurements from the GPS, DMSP, ESA's Meteorological Operational (MetOp), and NOAA's Polar Operational Environmental Satellites (POES) satellite systems provide particle flux data used in developing and validating models. They are also used in calculating radiation belt activity indices.

Expected results from this emerging opportunity are directly related to the PSGs discussed in Section C.2:

- *PSG 1:* The response of the magnetosphere to the time-varying solar wind input and the complex energy exchange between magnetospheric regions and with other regions of geospace are topics that require multipoint, multimodal measurements in the solar wind and geospace. Related science questions focus on magnetospheric plasma flow, particle acceleration, WPIs, and the onset and time evolution of plasma turbulence. Several aspects of these questions can be addressed by particle and field measurements at LEO, GEO, and other orbital regimes.
- *PSG 2:* Understanding the origins and impacts of cold plasma from the ionosphere and plasmasphere will benefit from distributed measurements in LEO and MEO, even from low-capability sensors. Prime examples include in situ particle precipitation at low orbits and the potential for radio occultation measurements to investigate the plasmasphere.
- *PSG 3:* M-I coupling is one of the main targets of leveraged science studies owing to the proliferation of commercial satellites at LEO. The structure and dynamics of high-latitude FACs and ionospheric current systems, of particle precipitation, and of low-frequency wavefield variations are significant research topics.
- *Implications for space weather modeling:* In addition, space weather-related science can benefit significantly from these measurements because commercial satellite systems are one of the primary users of space environment information. Synergies between commercial and research organizations have been exemplified in several research projects.

TABLE C-8 List of Current Commercial Constellations

Primary and Derived Measurements	Physical Processes	Constellation (Project)	Space Weather Relevance
Magnetic field Radial current density	Field-aligned current intensification and decay Related high-latitude electrodynamics	Iridium (NSF/AMPERE)	Geomagnetic disturbance development
Electron density, TEC, other parameters Charging diagnostics high-frequency noise	Particle precipitation Other magnetosphere–ionosphere coupling	Spire (NOAA/RO, DARPA/Ouija) PlanetIQ (NOAA/RO)	Spacecraft charging
Particle flux	Radiation belts: particle acceleration, transport, and loss	GPS	Spacecraft charging
Thermospheric density, O/N_2 ratio Ionospheric parameters	Thermospheric processes Ionospheric electrodynamics including magnetosphere–ionosphere coupling	Starlink	Satellite drag Spacecraft charging

NOTE: Acronyms defined in Appendix H.

The relation between measured quantities, the science involved, and benefits for space weather nowcasting and forecasting are myriad. Current constellations and their primary and derived scientific measurements, magnetospheric and ionospheric processes, and space weather relevance are presented in Table C-8.

Moving Forward

Agencies are continuing to develop these observational options through funding opportunities such as NASA's Commercial LEO Development (CLD) and Commercial Lunar Payload Services (CLPS) programs, and NOAA's Commercial Weather Data Pilot (CWDP) and Commercial Data Purchase (CDP) programs.

- *Use of commercial constellations and satellites in data purchases and hosting programs:* It is important to leverage the increased availability of commercial platforms, especially that of constellations, in magnetospheric regions and orbits such as LEO, MEO, GEO, and cislunar. In the future there may be opportunities for commercial satellites at high Earth orbit (HEO)—for example, for telecommunications or Earth observation. It is important to engage providers in government-commercial partnerships for data purchase and sensor hosting programs.
- *Open access to magnetospheric data sets:* It would be valuable to have access to data sets which have been compiled by government and/or commercial organizations, but owing to technical or programmatic reasons have not yet been accessible to the research community.
- *Development of standardized basic sensors:* Taking advantage of commercial flight opportunities would benefit from the development of a standard basic magnetospheric instrumentation payload for hosting on nonresearch platforms. Such instruments could include particle and plasma sensors, magnetometers, and compact multispectral imagers. Standardization of entry-level sensors will facilitate hosting on commercial satellites and could also be used for other programs that benefit undergraduate and early graduate research.

C.4.4 Leverage Low-Cost Ground-Based Sensors to Increase Spatial Resolution in Magnetospheric Measurements

In the past 10 years, the cost of several ground-based sensors has significantly decreased with commercial, mass-produced options increasingly available. Many of these options include the same types of sensors currently used by the magnetospheric research community, albeit in some cases with reduced accuracy, precision, or other capabilities. For example, in the past 10 years low-cost GNSS sensors that make use of multiple constellations are increasingly available and have been widely deployed and adopted for a range of investigations across the geosciences (e.g., cryosphere, seismology, and geodesy); this advance has enabled the development of higher spatial resolution TEC maps with fewer data gaps that are now a crucial research tool used for a range of scientific investigations. As another example, magneto-inductive sensors are a new magnetometer technology rapidly being developed for both space- and ground-based magnetic field measurements; these sensors are a fraction of the cost of the more widely used fluxgate magnetometers, and there are already plans for large deployments of these sensors as a ground-based student engagement component of the upcoming EZIE mission. As yet another example, low-cost, commercially available cameras that operate reliably in extreme temperature conditions open the possibility for more widely available aurora images.

The value of these low-cost sensors to PSGs 1–4 relates to the fact that for all these questions, increased spatial resolution and reducing data gaps is desirable. For example, PSG 1 requires measurements that resolve mesoscale structures in the ionosphere related to mesoscale flows and transients in the magnetosphere. Although existing and planned ground-based projects address this goal, they do so in a limited spatial region and with a limited spatial resolution. The incorporation of additional sensors would enable the study of phenomena across a wider range of spatial scales and spatial regions—for example, tracking the magnetic signature of fine structures in the aurora as they move equatorward during geomagnetic storms. Incorporating a significantly larger number of sensors, even if less precise/accurate than the more expensive sensors in wider use by the magnetospheric research community, would thus be a significant benefit.

Given that there are lower-cost versions of multiple sensors that are mainstays of solar and space physics research—GNSS receivers, magnetometers, all-sky cameras, ionosondes, and so on—efforts have recently begun to create multi-instrument platforms with multiple low-cost sensors. Analogous to platforms that are widely deployed by volunteers to study terrestrial weather, these platforms provide one avenue for significantly improving the ability to address PSGs 1–4. For the same reasons that current and planned multi-instrument platforms are being used to enable a wider range of investigations and the creation of higher-level data products (e.g., ionospheric conductance), multi-instrument low-cost platforms would open the door to a wider range of science investigations and potentially improve and/or validate the results found by the limited number of more expensive multi-instrument stations.

Taking the concept of low-cost ground-based sensors to the extreme, some measurements are available at zero cost from smartphones. The hardware in smartphones, including GNSS receivers that now routinely access multiple satellite constellations and more routinely available magnetic field measurements, have significantly advanced in the past 10 years. At the same time, artificial intelligence (AI) tools are now available that can conceivably identify and remove noise sources from these often less precise measurements. This is an emerging opportunity in the next 10 years, with initial efforts to analyze data from smartphones already under way.

Volunteers, also referred to as citizen scientists, are expected to play a key role in making the most of opportunities related to low-cost sensors. In the past 10 years, they have played key roles in early efforts to deploy low-cost sensors and perform pilot studies using these sensors. In the next 10 years, large-scale deployments of low-cost sensors analogous to what has already been done in the terrestrial weather (Personal Weather Station Network from Weather Underground), seismology (Raspberry Shake), and other communities could conceivably be achieved through volunteer support. These volunteers provide access to land, regular maintenance, valuable scientific contributions, and can potentially purchase the sensors to offset the cost of deploying the network.

C.4.5 Leverage Artificial Intelligence and Machine Learning to Advance Data Selection, Data Mining, and Empirical Modeling in Magnetospheric Physics

AI and machine learning (ML, subfield of AI focused on enabling computers to learn from data and make predictions or decisions without explicit programming) techniques have been increasingly adopted in magnetospheric research over the past 10 years, and this is only expected to increase in the next decade as the capabilities of these techniques continue to advance. There are several areas where ML techniques are already making key contributions to magnetospheric research, for example, using neural networks to model plasmasphere and radiation belt dynamics. Recent efforts have begun focusing on feature extraction from large data sets, using ML techniques to automate the detection of the electron diffusion region and other magnetospheric regions and boundaries.

The combination of improved AI techniques and the significantly larger data sets that are expected to become available in the next 10 years from both simulations and measurements lend themselves to several emerging opportunities.

Several of the planned missions will produce a significant quantity of data. As is the case with currently operating missions such as MMS, only a portion of these data can be returned, and so currently scientists examine low-resolution survey plots to determine which high-resolution data should be returned. AI techniques applied onboard the spacecraft are a powerful tool that enhances these capabilities. Most importantly, these tools have the advantage that they can be applied to the full resolution data onboard the spacecraft to determine which data segments should be returned to the ground, unlike the scientists on the ground who can only use lower-resolution survey data for their assessments. These advantages also apply to ground-based sensors deployed in remote locations where telemetry is similarly limited.

Several of the science questions require the identification of mesoscale phenomena that may be challenging to automatically identify in single instrument data sets. For example, the ground-based counterpart to an intense magnetospheric flow may be associated with different auroral forms from one event to the next. AI techniques can be developed that identify common features across multipoint, multi-instrument data sets to automatically identify desired phenomena using the full range of data sets available. This has the advantage that fewer events will be missed when analyzing large, multipoint, multi-instrument data sets where features may be more obvious in different instruments from event to event. In short, AI techniques will be powerful tools for data mining in the next 10 years and beyond.

ML techniques have also already been used as part of models that assimilate sparse data sets to develop models of radiation belt dynamics, plasmasphere dynamics, and so on. The increased spatial coverage afforded by several of the satellite and ground-based assets discussed so far presents a significant emerging opportunity for the development of more accurate models of a wider range of magnetospheric dynamics through data assimilation.

Last, measurements collected by satellite and ground-based instruments—especially the low-cost sensors discussed in the next section—are often noisy and affected by various sources of contamination that vary from location to location and event to event. AI techniques represent one tool for identifying and removing noise sources and contamination more thoroughly than existing techniques. Promising initial efforts have already been applied to sensors discussed in this report.

C.4.6 Leverage the Growing Capability of Supercomputers to Model the Magnetosphere

Numerical modeling of the magnetosphere system represents a grand challenge problem. First, the magnetosphere is a collection of coupled physical domains (system of systems), with each domain having very different physics and disparate length and timescales. Second, even within each separate domain, the plasma (and sometimes neutral) gas populations immersed in electromagnetic fields evolve on a wide range of length and timescales. Usually, the dynamics of the large (macro-), meso-, and microscale strongly affect each other, making the dynamics multiscale.

Even with these difficulties, significant gains have occurred in modeling capabilities in the past decade. For the first time, 3D global hybrid simulations of the magnetosphere are computationally accessible, allowing ion kinetic effects to be factored into the global magnetospheric dynamics. 2D and 3D fully kinetic simulations of reconnection, turbulence, and shocks are now regularly simulated that resolve microscales while extending all the way out to mesoscales. Global MHD coupling frameworks now regularly include more realistic inner M-I-T physics into the models, allowing direct determination of parameters such as aurora and ionospheric conductances. Whole atmosphere models that include the I-T can now resolve scales as small as 25 km in the horizontal direction.

However, addressing the full magnetosphere system of systems requires a new generation of models that (1) couple together models of individual systems or regions, and (2) resolve mesoscales while also incorporating the physics that govern microscales. Such simulations require unprecedented computing power. Fortunately, there are emerging opportunities in the coming decade in computational resources that will help facilitate scientific progress.

First, Moore's Law will likely continue into the next decade, allowing a continuous increase in computing power. Already, humanity has entered the era of exascale supercomputing with the first supercomputer, Frontier at Oak Ridge's Leadership Computing Facility, exceeding 10^{18} computations per second. Increasing processing power by more than a factor of 10 (following Moore's Law) would allow major advances in modeling the magnetosphere.

Second, graphical processing units (GPUs) have entered the mainstream and are widely available for scientific computing. GPUs accelerate processing speed by vectorizing calculations through a very large number of cores. However, modifying simulation models to use GPUs can require significant person-hours because memory access must be carefully planned to efficiently use GPUs. This barrier has prevented many widely used codes from being ported for GPU use.

In the next decade, scientists can build on the advances in model sophistication and leverage the nascent power of exascale supercomputing and GPUs to create the first generation of cross-scale holistic geospace models. Dedicated programs from NASA and NSF, including collaboration with the DOE which currently hosts exascale computing facilities, are needed to leverage these advances. Joint programs can facilitate development of models that are tailored to these heterogeneous architectures, as well as analysis and visualization tools that are able to ingest vastly larger amounts of modeling output volume. Accomplishing this leap forward will require a funding environment and heliophysics profession that can attract and retain a cross- and trans-disciplinary workforce spanning applied mathematics, physics, computer science, data science, and software engineering.

C.5 RESEARCH STRATEGY

C.5.1 Synopsis of Major Gaps

Having identified the priority and longer-range science goals and the emerging opportunities that can be leveraged, the following section outlines the research strategy needed to achieve the goals. Table C-9 summarizes the measurement and theoretical and modeling advancements that are needed in order to resolve each of the panel's PSGs. To address these needs, five missions and five facilities are presented that would promote significant progress on the science goals. In addition, areas where technology development is needed are identified, and collaborations between agencies, divisions and international partners that would strengthen the program are described. The use of existing and new assets and the role of the HSO in addressing the full system of the magnetosphere are discussed. Last, areas where investments in new programs and infrastructure are needed are identified.

C.5.2 Ability of Five Ground-Based and Five Space-Based Projects to Make Progress

The following mission concepts and projects have been identified as those that will move the magnetospheric community forward, closing the most gaps in the panel's PSGs.

Projects Most Ready to Make Real Progress

Space-Based Project: Links Between Regions and Scales in Geospace (Links)

The Links Between Regions and Scales in Geospace, or "Links," mission has the main scientific objective to understand the links between Earth's coupled M-I system, from energy input to the dayside to energy transfer from the nightside magnetotail to the aurora and ring current.

The Links mission will provide a detailed examination of the impacts of the near-Earth plasma sheet transition region, the dynamic region from 6–12 R_E where the magnetic field changes from dipolar to stretched. Diverse phenomena occur in this region including the interrelated: particle injections, dipolarizations, flow braking and deflection, magnetic flux pile-up, generation of the substorm current wedge or wedgelets, and FAC generation. This transition region between the plasma sheet and inner magnetosphere acts as the "gateway" to the inner magnetosphere, providing the population that creates the ring current that drives geomagnetic storms as well as seeding particles that fill the radiation belts. It is also where many intense auroral forms are driven, as flow braking and dipolarization drive FACs that cause aurora, and more recent results suggest it is where an instability forms that creates a bead-like structure on the substorm's quiet auroral arc. The links between this transition region and both the aurora and the inner magnetosphere are main foci of this mission.

Another focus is the link between the solar wind and the dayside magnetopause. It is known that dayside reconnection is a primary mechanism for transferring energy from the solar wind to the magnetosphere, and much

TABLE C-9 Future Needs Required to Address the Priority Science Goals (PSGs)

		Future Needs	
Priority Science Goals	Objectives	Measurement	Theory/Modeling
PSG 1. How is the solar wind energy input to the magnetosphere transmitted between different regions and across different scales?	**1.a.** Scale size and evolution of transfer processes at the magnetopause **1.b.** Transport, storage, and release of energy in the nightside plasmasheet **1.c.** Connection between plasmasheet and auroral structures	• Magnetic field, plasma density and velocity along the dayside magnetopause with spatial resolution of 0.5 R_E spanning a spatial region or FOV of 4–5 R_E. • Multipoint plasma, energetic particle, and fields observations across multiple scales spanning 2–15 R_E radially from Earth on Earth's nightside. Azimuthal separation distance of $\leqslant 1$ R_E, spanning >5 R_E. • Fine spatial resolution (<1 R_E) plasma imaging of 2–15 R_E radially from Earth and MLT = 0 ±4 hours. Temporal resolution of <60 s. • Network of ground-based of imagers, magnetometers, and radars, spanning >4 hours local time and 40 to 80 degrees magnetic latitude (MLAT), horizontal resolution <20 km and time resolution <60 s. • Simultaneous auroral oval imaging of both hemispheres: measure energy flux, mean energy, and conductance from precipitation, resolve auroral structures <50 km wide. • Magnetic field line mapping between magnetosphere and ionosphere within 20 percent accuracy.	• Global magnetosphere models incorporating the physics and the requisite resolution to capture nightside and dayside reconnection and boundary instabilities, including effects of heavy ions. ◦ Magnetospheric coupling to the ionosphere with the corresponding spatial and temporal resolution. • Improved self-consistent coupling of global magnetospheric models of the inner magnetosphere and the nightside transition region. • Global magnetosphere models including M-I coupling and improved precipitation models with the requisite resolution to capture discrete auroral forms and their drivers in the plasma sheet.
PSG 2. What are the characteristics, life cycle, and magnetospheric impact of plasma of ionospheric origin—both the cold populations and hotter energetic outflows?	**2.a.** Plasmasphere formation and evolution **2.b.** Drivers and pathways for Ion outflow **2.c.** Magnetospheric impacts of ionospheric plasma **2.d.** Ultimate fate of ionospheric-source plasma	• Composition, energy, angular distributions of cold ions and electrons (<eV) throughout the magnetosphere, including: plasmasphere, lobes, and magnetotail. • High mass resolution ion composition (e.g., to distinguish O^+ from N^+) for cold (<eV) and warm (~eV–keV) ion populations throughout the magnetosphere. • In situ (plasma, field, and wave) and remotely sensed/derived (e.g., ambipolar electric field, ion pressure gradients) measurements at multiple latitudes and altitudes throughout the exobase transition region (~350–1,500 km). • Simultaneous measurements of plasmaspheric density, composition and spatial structure. • Simultaneous measurements at low (<2,000 km) and high ($\geqslant 3$ R_E) altitudes to capture ion transport/evolution from ionospheric to magnetospheric regions.	• Self-consistent modeling of cold and hot populations. • Global models to capture kinetic and nonadiabatic aspects of transport to and in the plasma sheet. • Coupling of ionosphere and magnetosphere models.

PSG 3. What controls the multiscale electrodynamic coupling between the ionosphere and magnetosphere?	**3.a.** IT response to magnetospheric and solar wind input **3.b.** Effects of ionospheric state on M-I coupling **3.c.** Physical processes controlling field-aligned currents **3.d.** Drivers of auroral forms and airglow	• Co-located measurements of the following fundamental ionospheric parameters at $\geqslant$45 degrees magnetic latitude, $\leqslant$1-minute cadence, and mesoscales ($\leqslant$500 km horizontal scale across several hours of local time, ~100 km horizontal scale in smaller regions): ◦ Ionospheric current ◦ Low energy precipitation ◦ High energy precipitation ◦ Ionospheric electron density ◦ Ionospheric conductance • Global-scale ionospheric current in both hemispheres at $\leqslant$10-minute cadence. • Meso- and global-scale ionospheric flows in both hemispheres at $\leqslant$1-minute cadence. • Volumetric measurement of ionospheric density, flow, and other parameters in the polar cap, auroral zone, and mid-latitude region at <10-minute cadence. • Horizontal and vertical neutral winds at meso- and global scales, $\leqslant$10-minute cadence.	• Altitude-resolved ionospheric models. • Global simulations that seamlessly blend high-, mid-, and low-latitude regions. • Incorporation of inductive M-I coupling into models.
PSG 4. What are the 3D global properties of turbulence, magnetic reconnection, and shocks, and what is their role in coupling energy in the magnetosphere?	**4.a.** Reconnection region formation and evolution **4.b.** Interplay among turbulence, reconnection, and shock dynamics **4.c.** Energy partitioning across bow shock **4.d.** Feedback between macro and micro scales	• 3D magnetic and electric fields, plasma moments, and energetic particles (tens of keV-MeV) capturing meso-scales (0.1–1 R_E) and microscales (hundreds of km) in the magnetosheath and along the dayside magnetopause. • Particle distribution functions (at a minimum electrons, H^+, and He^{++}) upstream of the bow shock in the solar wind and downstream of the bow shock in the magnetosheath simultaneously.	• Mesoscale or global simulations which include kinetic microphysics: Global hybrid simulations include kinetic ion physics but are computationally expensive; embedding of kinetic simulations in global models is another avenue of research.
LRG. How do other planets' magnetospheric characteristics and configurations affect their magnetospheric processes, interactions, and dynamics?	**LR.a.** Common processes across planetary magnetospheres **LR.b.** Variations in planetary systems and effects on magnetospheric characteristics **LR.c.** Scaling laws for fundamental magnetospheric processes	• Magnetospheric plasma and energetic particle (tens ke–V–MeV) populations, including composition, and electromagnetic fields from each planetary system across wide ranges of radial distances, magnetic latitudes, and local times. In particular: ◦ In situ measurements at Uranus and Neptune ◦ Energetic particles at Jupiter ◦ Upper atmosphere at Venus • Long-baseline measurements to compare and contrast diurnal, seasonal, and solar cycle variations of solar wind-magnetosphere coupling at each planet. • Auroral, airglow, kilometric, synchrotron, ENAs, and other emissions relevant to gain insight into magnetospheric processes and M-I coupling at each planet.	• Advancements in MHD models of other planetary magnetospheres to allow more direct comparisons to those of Earth. • Simulations of outer planet radiation belt populations via test particles in underlying magnetohydrodynamic fields, as has been performed for Earth.

NOTE: Acronyms are defined in Appendix H.

progress on the mechanics has been made with the MMS and THEMIS missions. However, researchers have yet to determine quantitatively the extent and temporal evolution of magnetopause reconnection, which requires a mission with magnetopause imaging capabilities and/or multipoint in situ measurements with a spacing on ion- and MHD-scales (thousands of km to ~1 R_E) and separated along the magnetopause boundary. Mapping the knowledge of local reconnection physics to a potentially spatially extended process spanning many R_E across the magnetopause remains a major understanding gap which could be addressed by an array of spacecraft with ion to MHD-scale spacing. The Links mission can also study the spatial extent of kinetic transients from the shock and magnetosheath such as hot flow anomalies (several R_E) and magnetosheath jets (0.5 R_E), important phenomena that have been observed to cause dramatic (many R_E) distortions of the magnetopause and trigger magnetic reconnection locally. Although these structures are known to exist, their global impact on the flow of energy into and through the magnetosphere and ionosphere is linked to their temporal frequency and spatial extent which has not been observed.

Although the list of science questions that Links could address is exciting and long, the consolidated main science objectives are the following:

- Determine how plasma sheet mesoscale structures transport and energize particles from the plasma sheet to the inner magnetosphere.
- Determine how much and under what conditions mesoscale structures contribute to the build-up of the ring current.
- Determine how the aurora and conductance in each hemisphere respond to multiscale plasma sheet structures and their evolution.
- Determine quantitatively the extent and temporal evolution of magnetopause energy coupling as functions of solar wind and magnetosheath conditions and associated driving structures.

The objectives will be met with a combination of at least 24 in situ satellites—eight spacecraft each on three elliptical, low-inclination (~10°) orbits—along with at least two imaging satellites along a singular 9 R_E circular polar orbit, as illustrated in Figure C-7. The baseline mission duration is 3 years. The three low-inclination elliptical orbits are in resonance to capture the spatial progression of the various phenomena listed above in the transition region with target apogees and perigees of ~8.24 $R_E \times 1.49$ R_E, ~10.79 $R_E \times 1.29$ R_E, and ~15 $R_E \times 1.11$ R_E. At apogee, the in situ satellites have 1 R_E spacing across ± 5 R_E to capture and constrain the meso-scale phenomena. (Note that the along-track spacing can be adjusted for different mission phases.) This spacing can capture and constrain the 1–3 R_E wide mesoscale flow bursts/DFBs. The orbits will precess together, taking approximately a year to complete a full precession.

For at least one dayside season, as they precess along the flanks toward the dayside, the in situ satellites will use a small amount of fuel to reduce their along-track separations such that the satellites have 0.5 R_E spacing near apogee. This smaller spacing is driven by the scale sizes of the features under investigation. On the nightside, mesoscale flows and their related dipolarizing flux bundles and current wedgelets are ~1–3 R_E wide. On the dayside, magnetosheath jets are on the order of 0.5 R_E across. Hot flow anomalies are ~3 R_E across, meaning that 1–2 of the 3-year baseline may not require any maneuvering between nightside and dayside, keeping the spacing at 1 R_E.

All of the in situ satellites will carry an ion and electron plasma instrument (e.g., electrostatic analyzer covering ~2 eV–32 keV), an energetic particle instrument (e.g., solid state telescope covering ~30 keV to several MeV), and a fluxgate magnetometer. This instrument suite enables them to measure plasma flows, particle injections, dipolarizations and dipolarization flux bundles, and the V×B electric field.

The imaging spacecraft will be in polar orbits with ~9 R_E apogee in order to image both the auroral oval and the plasma sheet and transition region. The two spacecraft will be co-orbital but with different phasing throughout the 3-year mission lifetime. During part of the mission, the spacecraft will be separated by about 90 degrees to allow for extended coverage of the auroral oval in one hemisphere. In another mission phase, the two spacecraft will be separated by 180 degrees to image both the northern and southern hemispheres simultaneously, allowing Links to determine interhemispheric asymmetries in the aurora that may play a key role in unfolding M-I coupling processes.

Each will carry two FUV imagers with different wavelengths (140–160 nm and 160–180 nm), which will be used to observe the aurora and to measure the precipitating energy flux and mean energy that is deposited into the

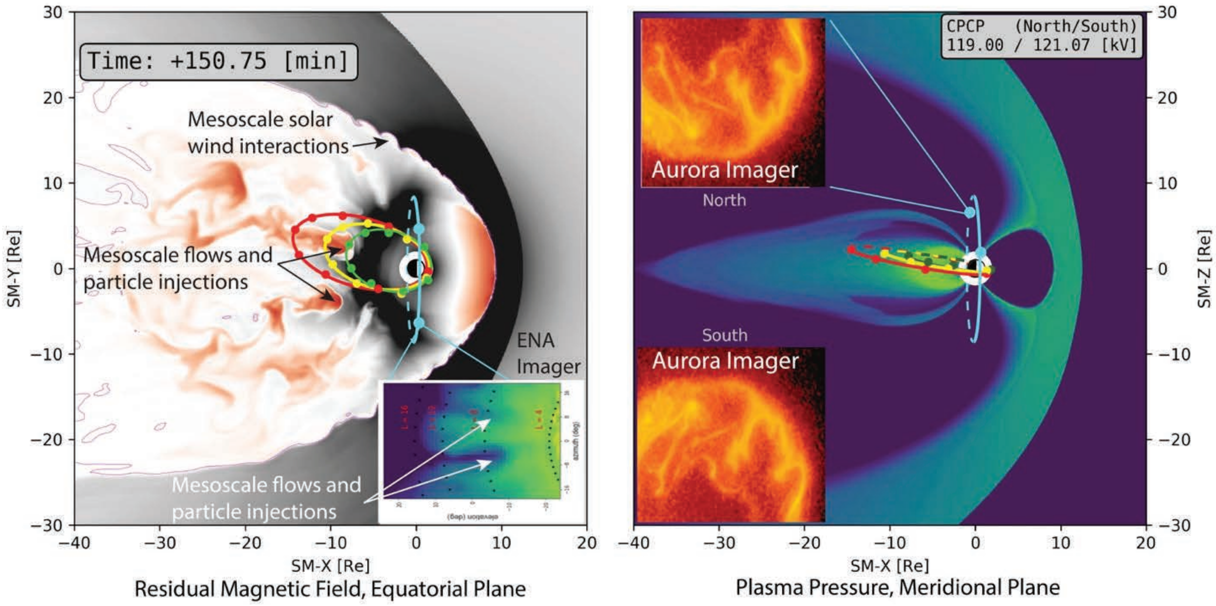

FIGURE C-7 Illustration of the Links mission spacecraft configuration in the magnetospheric X-Y and X-Z planes. SOURCES: Modified from Sorathia et al. (2020), https://doi.org/10.1029/2020GL088227. CC BY 4.0; Auroral images courtesy of Los Alamos National Laboratory, Department of Energy, https://doi.org/10.13140/RG.2.1.4976.9688.

ionosphere from the magnetosphere. They will have a ~20 km resolution at nadir in order to resolve the smallest meso-scale auroral streamers. FUV wavelengths can image both the nightside and the dayside, meaning precipitation will be imaged even on the sunlit side, providing 2D context for dayside events. The FUV imagers will also be used to derive 2D conductance measurements, which are important for M-I coupling studies. For example, precipitation increases conductance, and larger conductance decreases ionosphere plasma flow speeds and the related electric fields. This feeds back to the magnetosphere and has been shown via simulations to alter magnetospheric phenomena–like where reconnection in the tail occurs. The FUV imagers will also observe the auroral manifestation of the various phenomena occurring in the tail, like streamers (North-South aligned equatorward-moving arcs caused by fast earthward-traveling plasma flows), the substorm onset arc and its poleward expansion (initiating somewhere in the magnetotail transition region), and so on.

In addition to the FUV imagers, the polar orbiting spacecraft will also carry three ENA imagers: two narrow-angle ENA cameras (oriented orthogonally) to view the plasma sheet with a 50° × 50° field of view centered on the Sun–Earth line, and one wide-angle ENA camera for viewing the ring current with a 90° × 120° field of view. The magnetotail is wide compared to the size of the meso-scale structures of interest (~40 R_E versus 1–3 R_E). Thus, even with 24 in situ satellites, knowing the context of the phenomena (such as fast earthward flows) would be difficult without some form of 2D imaging. For example, studies that have used up to 16 in situ satellites to study particle injections have found it difficult to fully constrain their azimuthal size and penetration depth. Because flows can divert azimuthally, it may be hard to distinguish whether a flow stopped before reaching the inner orbit or if it was diverted elsewhere. Ground-based ASIs have been used to provide 2D context, assuming that equatorward-traveling auroral streamers are caused by earthward-traveling plasma flows in the plasma sheet. Although great results have been derived from this technique, the exact mapping from the ionosphere to the magnetosphere is in question whenever discrete aurora are involved. Lastly, to estimate the ring current enhancement owing to meso-scale particle injections, several assumptions must be made that make the answer difficult to determine, even with multiple in situ satellites flying within the ring current.

ENA imaging provides not only a global image of the plasmas in space, but also compositional and spectral information about the parent ion population (3–300 keV protons, 20–300 keV O^+). It is currently the only technique capable of imaging the ion population in the plasma sheet and ring current. Present ENA instrument limitations result in low counting statistics, only allowing for few to tens of minutes time-averaged measurements, rendering exploring the mesoscale, fast-moving mode of transport practically impossible. The narrow-angle ENA imagers on Links would provide temporal resolution of <60 s and spatial resolution of <0.5 R_E. With a view downtail, they would therefore provide the 2D context to definitively determine whether the in situ satellites are observing the same structure propagating between their three (3) orbits. It would also provide information on the structures' scale sizes and velocities. The wide-angle ENA imager looking at the ring current would measure its enhancement with <1 R_E spatial resolution and <300 s temporal resolution.

The combination of both FUV and ENA imagers will also assist with connecting magnetotail observations to ionosphere observations. The objectives do not require perfect mapping knowledge, which is quite difficult. However, with ENA imaging providing context with regards to the frequency and locations of heating in the tail, changes in auroral structures and conductance that form in the same MLT sectors can be linked.

Links fits well within the STP program. Links is studying the fundamental physical processes that determine the mass, momentum and energy flow, consistent with STP program goals. Furthermore, understanding the impact of the dynamics at mesoscales would lead to significant broad-based scientific progress for the field, another STP qualifier. However, Links also has aspects of an LWS mission. Incorporating the mesoscales into future (or current) models would be a new system science capability which could lead to better operational space weather prediction.

Links could be upscoped by adding one additional polar orbiting imager to enable constant comprehensive coverage of the auroral oval. It could also be upscoped by adding four additional in situ satellites per orbit, for a total of 36 in situ satellites to enable a faster revisit time of the region of interest. The baseline Links mission comprises 24 in situ satellites assuming 80 percent resiliency, which allows for modest cost saving in the spacecraft design and can accommodate the loss of 1–2 in situ satellites per orbit (i.e., ~20 total operational in situ satellites). This worst-case scenario would decrease the revisit time as well as remove valuable data points. As mentioned, previous studies have used ~16 ad hoc satellites from the HSO and other assets in conjunction to study meso-scale injection events with limited results.

Although Links would meet its science objectives with the proposed instrumentation and spacecraft, it would be greatly enhanced by the ground-based facilities proposed in this report. In particular, the Distributed Network (discussed below) provides multiple avenues for science enhancement. For example, the ASI network can provide auroral information such as precipitated particle energy flux and conductance in 2D and be intercalibrated with ground truth measurements from IS radars at higher spatial and temporal resolution than Links's UV imagers will have off-nadir. The Links data set, which will contain conductance values estimated from the short and long Lyman-Birge-Hopfield (LBH) bands that can also be intercalibrated with IS radar measurements, could also potentially be cross examined and cross calibrated to establish the cross-scale distribution of the deduced precipitating characteristic energy and energy flux. Furthermore, when Links's two imaging spacecraft are separated by 180°, the ASIs may provide continuous coverage while the Links spacecraft are not above the poles. The ground-based magnetometers would be instrumental in measuring the currents related to the mesoscale features Links is studying, further helping us understand the electrodynamic coupling between magnetosphere and ionosphere. The riometers would provide the ground-based view of particle injections. They have been used to constrain the injection location in space as well as their azimuthal width, generally showing a localized precipitation increase that spreads azimuthally, poleward, and equatorward. Having a network of riometers would support Links's objective to understand how injections contribute to the ring current as well as the additional objective of understanding the coupling between magnetosphere processes and the ionosphere's response. The TEC values provided by GNSS receivers distributed across North America provide a similar data point, demonstrating where more electrons are being deposited.

SuperDARN is also science-enhancing for Links, as it provides 2D measurements of the ionosphere plasma flows that form thanks to their magnetospheric counterpart, the meso-scale fast plasma flows in the tail. They have been correlated with the meso-scale, equatorward traveling auroral streamers, which are the visible footpoint of those magnetotail plasma flows. SuperDARN therefore can support Links by providing characteristics and statistics of these flows, which are not only a proxy of the magnetosphere flows but also an observable way that the ionosphere responds to magnetospheric input. This supports the system science Links is performing, linking the magnetosphere to the ionosphere (and can be further used in models of the thermosphere).

The Links mission is clearly focused on PSG 1: the energy, mass, and momentum transfer between the solar wind and magnetopause, between the magnetotail plasma sheet and the inner magnetosphere, and between the magnetosphere and the ionosphere. Links was designed to address the important outstanding questions connecting these systems within the larger magnetospheric system.

Links also contributes significantly to PSGs 3 and 4. For Goal 3, Links will measure the ionospheric conductance in 2D, addressing the objective to determine how the state of the ionosphere affects M-I coupling. In addition, it will address the coupling between the magnetotail transition region and the auroral region which directly address the subquestion: "What are the drivers of the different auroral forms and airglow?"

For Goal 4, the Links observing capability will enable a wide range of compelling research into how plasma and energy from the solar wind is processed in through the shock and magnetosheath and then coupled into the magnetosphere. The cross-scale spatial properties of reconnection could finally be probed. The in situ spacecraft would enable definitive measurements of the varying spatial extents of magnetopause reconnection as well as temporal dynamics, such as reconnection growth and which characteristics control it. Also critical for quantifying the energy input into the magnetosphere and producing a global energy budget is a measure of the efficiency of reconnection as a function of position along an x-line or reconnecting separator. Beyond magnetic reconnection, the cross-scale coupling and the impact of waves and large-scale structures along the magnetopause boundary would also be probed. Boundary instabilities such as Kelvin-Helmholtz (KH) waves are routinely observed by in situ spacecraft along the flanks of the magnetopause, yet the complicated cross-scale physics of nonlinear KH waves make it challenging to evaluate their role in accelerating plasma, triggering ULF and other plasma waves, or transferring mass and energy into the magnetosphere. The differential micro- to macro-scale spacing with the in situ Links spacecraft along the flank magnetopause would enable the measurements necessary to answer these questions.

Upstream of the magnetosphere, magnetosheath and shock kinetic physics will also be studied. A diverse set of structures and discontinuities develop through small-scale kinetic instabilities such as foreshock cavities, magnetosheath jets, hot flow anomalies, Short Large-Amplitude Magnetic Structures (SLAMS), solitons, and density holes. After forming, most of these transient magnetosheath structures travel downstream and collide with the magnetopause. A major problem is understanding how these structures grow, evolve, and couple energy into geospace. When apogee of the Links petals is on the dayside, the constellation will permit the community to measure the evolution of these structures from meso-scale to macro-scale and their interaction with the magnetosphere.

Space-Based Project: SOURCE

The Synchronized Observations of Upflow, Redistribution, Circulation, and Energization (SOURCE) mission concept consists of five spacecraft in four different orbital regions to track plasma flows from the ionosphere and through the magnetosphere, as shown in Figure C-8. The primary science goal of SOURCE is to understand the processes and pathways by which core magnetospheric ions flow from the ionosphere and are energized and redistributed within and throughout geospace. To accomplish this goal, the mission targets four more specific science objectives:

- Determine how magnetospheric and solar energy inputs cause outflow of ionospheric plasma into the magnetosphere.
- Determine the mechanisms that drive refilling and isotropization of the plasmasphere.
- Determine the pathways of core plasma transport and energization through the lobes and tail to help create the plasmasheet, warm plasma cloak, and ring current.
- Understand how the plasmasphere is eroded and redistributed during disturbances.

Core plasma is defined here as that which originates in the ionosphere and is initially cold (<10 eV) but may become heated (to ~10s eV or keV) through various energization and transport mechanisms as it permeates the magnetosphere.

Owing to the inherently cross-energy, cross-regime, and cross-scale nature of these questions, the mission concept uses five spacecraft, with both imaging and in situ instrumentation, to piece together a full picture of the system. The first two spacecraft (M1 and M2) are identical in situ spinning observatories in LEO spanning the

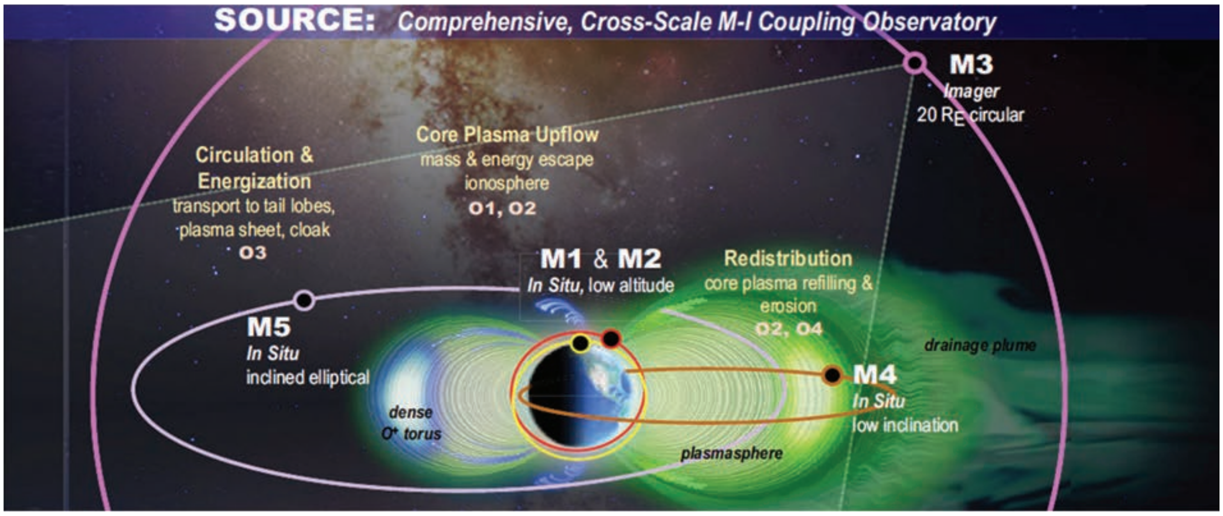

FIGURE C-8 Illustration of the SOURCE mission spacecraft configuration and key science objectives.
SOURCE: Goldstein et al. (2023), https://baas.aas.org/pub/2023n3i132/release/1. CC BY 4.0.

exobase transition region (ETR) (~350–1,500 km altitude). Their slightly elliptical orbits are phased in such a way to achieve conjunctions along the field line at high latitudes, allowing for tracking of ion distributions and energy inputs versus altitude and time. This distinguishes it from past measurements such as those from FAST or Polar, which could only study ion outflow outside the ETR, and thus were unable to determine the mechanisms controlling atmospheric escape. These spacecraft will measure electron and ion distributions, including ion composition, from fractions of eV to tens of keV, as well as magnetic and electric fields and waves, to directly address the missions' first science objective—how core plasma escapes the ionosphere.

The third spacecraft (M3) is a nadir-pointing imaging spacecraft in a 20 R_E circular polar orbit, to provide global to regional-scale imaging of refilling, evolution, erosion and circulation of core ions in the plasmasphere and O^+ torus. To do so, it is instrumented with EUV imagers at two wavelengths (similar to those on IMAGE), an ENA suite consisting of low- and medium-energy instruments (similar to those from JUICE and TWINS), as well as a geocoronal imager (such as those on ICON and the Carruthers Geocorona Observatory). Together these instruments will produce system-level observations of the plasmasphere and ring current, the formation and structure of the O^+ torus, and quantified exospheric neutral hydrogen variability, important for regulating upward light ion escape. A GPS receiver will also be included onboard M3, to be combined with existing GNSS assets to measure TEC between the spacecraft. These measurements can complement and validate densities derived from EUV line-of-sight imaging.

To complement the remote sensing observations on M3, the fourth spacecraft (M4) is a Sun-pointing spinning spacecraft, this time in a near equatorial geotransfer-like orbit, similar to that of the Van Allen Probes (~1.1 × 5.8 R_E). It includes a fields suite, to measure magnetic and electric fields and waves (same as on M1 and 2), as well as a plasma instrument (similar to that on Van Allen Probes) to capture direct measurements of ion density and composition, to constrain the remote observations produced by M3. One modification from the previous Van Allen Probes instrument design would be inclusion of a Sensor-Panel-Bias system to enable direct measurements of the coldest, ~0 eV ions. The in situ observations provided by M4 will be able to measure cold ion refilling, heating, composition, and transport in the plasmasphere, O^+ torus, and trough regions, thus helping address second and fourth mission science objectives.

The fifth and final spacecraft (M5) is also an in situ spinner, but in a higher-altitude, elliptical, and more inclined orbit at ~4 × 15 R_E. The aim is to have M5 in the same orbital plane as M1 and M2, such that it can measure outflowing ions that have been energized and transported in the lobes, plasma sheet, and cloak. It again includes the Fields Suite (like M1, M2, and M4), as well as hot electron measurements in addition to comprehensive measurements of ion distributions, including ion composition, from fractions of eV to tens of keV. The addition of this M5 spacecraft, in coordination with measurements from the other four, helps address the third mission science objective, to track core plasma through its energization and circulation cycle deeper in the magnetosphere.

The SOURCE mission is well suited to the LWS mission line. Core plasma is a critical component of the space environment, controlling wave growth and WPIs that can enhance or deplete the radiation belts, or impact spacecraft charging. Better understanding of the processes and pathways by which core plasma flows from the ionosphere would lead to significant model developments to improve space weather prediction and forecasting. This mission concept also has some aspects relevant to the STP Program. It addresses the fundamental processes of ion acceleration across the exobased transition region as well as those driving plasmaspheric refilling, isotropization, and erosion. Progress on all these processes would advance the understanding of fundamental physics present throughout solar and space physics.

While some components of the SOURCE mission, for example, could be accomplished at the individual level by smaller-scale missions, one of the primary benefits of the five-spacecraft mission as described here is the system-level contributions it will be able to provide.

The SOURCE mission science goals and objectives directly address PSG 2, in particular objectives 2a, 2b, and 2d, and would lead to substantial progress in the understanding of the characteristics, life cycle, and magnetospheric impact of plasma of ionospheric origin.

However, the SOURCE mission also plays a role in addressing PSG 1. SOURCE is a systems-level mission that targets the full life cycle of core plasma, from its ionospheric origin to its magnetospheric energization and impact. It uses imaging to quantify the distribution, composition, system-level transport, and dynamics of core plasma. In situ measurements capture the local transport and physical processes that are responsible for creating highly structured core plasma distributions of the plasmasphere, dense O^+ torus, and warm cloak. Understanding the mass coupling between the ionosphere and the magnetosphere will be a major advance in the understanding of geospace, addressing objective 1a. SOURCE takes us beyond electrodynamic M-I coupling to consider a key knowledge gap: the mass exchange side of the interaction. SOURCE's major innovation is a cross-scale, start-to-finish understanding of this mass coupling and its profound impact on the magnetosphere—that is, how ion outflows are generated, how they are trapped, and their transport pathways and contribution to hot and cold plasma populations.

In addition, SOURCE also plays a role in addressing PSG 3. The M1 and M2 spacecraft will examine the details of the escape of plasma owing to energy inputs from the magnetosphere, addressing objective 3a: "What is the response of the ionosphere/thermosphere system to magnetospheric and solar wind input?"

Space-Based Project: OHMIC

The Observatory for Heteroscale Magnetosphere–Ionosphere Coupling (OHMIC) consists of four spacecraft that combine high-time-resolution plasma and fields measurements in the auroral acceleration regions (AARs) with high-resolution local and global auroral imaging. The primary science goal of OHMIC is to discover how electromagnetic energy is converted to particle energy to power the aurora and ionospheric outflows. To accomplish this goal, the mission targets three more specific science objectives:

- Determine how energy conversion and transport vary along the magnetic field.
- Determine how ionospheric outflow is mediated by ion heating, convection and field-aligned transport.
- Determine how coupled parallel and perpendicular dynamics regulate energy conversion in discrete aurora.

These mission science objectives directly address PSG 2 and would lead to substantial progress in the understanding of the characteristics, lifecycle, and magnetospheric impact of plasma of ionospheric origin.

The OHMIC mission utilizes a fleet of four spacecraft to comprehensively study the auroral region of the magnetosphere. Figure C-9 illustrates three of the four spacecraft. Two spacecraft identically instrumented for in situ measurements of particles and fields fly through the auroral regions at ~6,000 km altitude with magnetic field-aligned separations varying from 10 to 1,000 km. One satellite with an Ultraviolet Imaging Instrument co-orbits with the upper in situ spacecraft providing images of the magnetic footpoint. A second imaging satellite

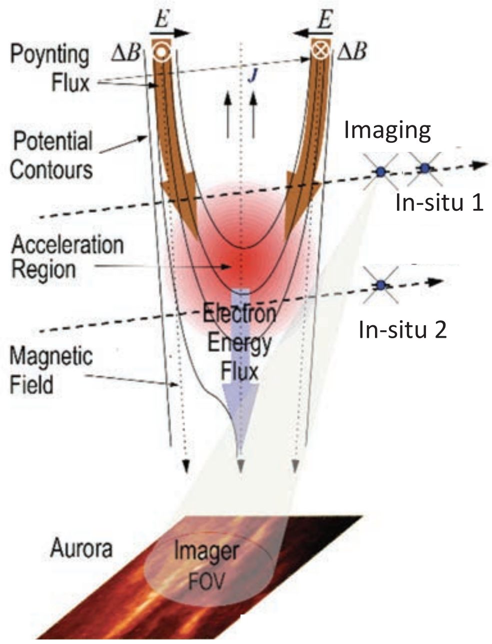

FIGURE C-9 Illustration of the OHMIC mission spacecraft configuration for three of the four spacecraft. A fourth spacecraft to image the aurora at a larger scale is in an orbit with apogee of 8 R_E.
SOURCE: Burch et al. (2023), https://baas.aas.org/pub/2023n3i041/release/1. CC BY 4.0.

orbits with an apogee of 8 R_E, providing global images of the aurora. Unlike previous missions that relied on a single spacecraft, this approach enables two spacecraft to measure temporal variations and spatial structures in situ, while the other two perform global and local auroral imaging with high resolution.

In order to fully understand the process by which electromagnetic energy is transformed into particle kinetic energy, it is necessary to accurately measure the changes in energy conversion and transport along the geomagnetic field. The field-aligned gradient scale lengths and characteristic plasma scale lengths play a pivotal role in determining the processes responsible for auroral particle acceleration. Obtaining measurements at two points with magnetic field separations of different length scales is required to gain a comprehensive understanding of how electromagnetic energy is converted into particle kinetic energy to produce the aurora.

OHMIC uses a combination of plasma and field measurements, along with auroral imaging, to study the energy conversion and particle acceleration in auroras. This is done by capturing images of the auroral morphology and energy flux using multispectral cameras on a three-axis stabilized satellite. The "triple conjunction" strategy enables OHMIC to determine the electron energy flux at three different altitudes, which provides critical information about the physics of auroral energy conversion and particle acceleration. The orbital strategy of OHMIC uses the differential apsidal precession rates of two satellites to achieve inter-satellite separations along field lines ranging from 10 to 1,000 km.

The instrumentation, which has a high heritage from previous missions such as IMAGE, FAST, ICON, MMS, Van Allen Probes, and Juno, includes a plasma instrument, an electromagnetic fields instrument, and a UV imager. The plasma instrument measures 3D distributions of electrons and ions (with composition) over an energy/charge range of 1 eV to 40 keV at a time resolution of 0.1 s. The fields instrument measures 3D AC, DC electric, and magnetic fields (DC to 1 MHz) and plasma density at 0.1 s. The UV imager measures LBH total (140–180 nm) and LBH long (160–180 nm) photons with a field of view of 8°, an angular resolution of 0.03°, and a time resolution of 10 s. Because of their heritage, no technological developments are needed.

The OHMIC mission will address basic research in the category of planetary ionospheres/upper atmospheres and so falls best within the STP Program. This mission concept concentrates on closing a knowledge gap on understanding how inflowing energy drives the aurora and ion outflow. Advancements in these processes would greatly improve the understanding of particle acceleration, both in the auroral acceleration region, but more generally throughout the heliosphere.

OHMIC addresses an aspect of PSG 2 that is not met by the SOURCE mission. While the two low-altitude SOURCE spacecraft (M1 and M2) address the ion heating that causes the upflow of ions, it does not include the further acceleration, distributed along the field line that converts upflow to outflow. Understanding this additional acceleration is critical to understanding the source of heavy ions to the magnetosphere.

In addition, OHMIC addresses PSG 3. By measuring the relationship between auroral energy input, the resulting acceleration, and the local and global auroral features, OHMIC determines the role of the ionosphere in driving ion outflow. By distinguishing the importance of the different acceleration processes and their relationship to the auroral features, OHMIC examines the fundamental physics involved in M-I coupling.

Space-Based Project: MAKOS

One area of opportunity highlighted for focused study in the next decade is collisionless shock physics. One example of a mission with the ability to make major progress in the understanding of the processing of material through shocks is the Multi-point Assessment of the Kinematics of Shocks (MAKOS) mission. The mission concept provides multipoint spacecraft measurements with the goal to unravel outstanding fundamental physics questions linked to shocks and energy partition. The mission would provide comprehensive measurements of particles and electromagnetic fields with a pair of spacecraft upstream and a second pair downstream of the terrestrial bow shock to quantify the partitioning of energy through a collisionless shock as well as the driving physics. One potential question to address is how is energy partitioned across a collisionless shock and what may control these processes? Figure C-10 illustrates the dynamic region that is the focus of the mission and the planned spacecraft configuration. Each pair of spacecraft just upstream and downstream will orbit with varied inter-spacecraft spacing ranging from ion-scale (100–1,000 km each pair) to MHD-scale (several R_E) to probe developing 3D physics linked to the shock. For particles, each spacecraft would carry an identical suite of instruments capable of measuring and resolving the core of the solar wind particle distribution, particles with energies ranging from cool to suprathermal as well as minor species such as He, C, N, O, and Fe. To monitor waves, each spacecraft would carry identical instruments to measure 3D DC and AC electric and magnetic fields. A number of mechanisms have been proposed to partition the energy through the shock including cross-shock electrostatic potential, current-driven instabilities such as the Buneman and electron-cyclotron drift instability, magnetic reconnection, and other WPIs, and particle acceleration and reflection. The balance and varying roles of these mechanisms, as well as their coupling between spatial scales, remain unknown and could be probed by the MAKOS mission.

Although collisionless shocks are one of the few fundamental mechanisms that process and accelerate plasma throughout the universe, the community has lacked the necessary experimental measurements to quantify how material and energy is processed through the boundary. The solar and space physics environment offers a front-row seat where detailed, multipoint, in situ measurements can be made to provide insight that can be applied to a wide range of systems. With a variable incident solar wind, regular measurements from a dedicated mission can probe the physics over a wide range of plasma beta and Mach number, as well as incident magnetic field geometries.

The broad, wide-ranging physical understanding which would be enabled within the heliosphere and throughout the universe places the MAKOS concept most closely within the STP resource line for space-based missions.

The MAKOS mission directly addresses PSG 4. Shocks are a fundamental physical process. Understanding shock properties and key physics governing them are the focused goal of this mission. The multispacecraft measurements will lead to the discovery of the kinetic physical processes and their spatial properties. The results from MAKOS on particle acceleration at shocks would have universal applications in many astrophysical environments.

Space-Based Project: COMPASS at Jupiter

As detailed previously, the Longer-Range Goal focusing on comparative planetary magnetospheres has been supported by operating ground- and space-based missions and facilities funded by NASA and NSF at Earth and beyond. While these assets have made significant advancements in addressing system-specific questions, they have

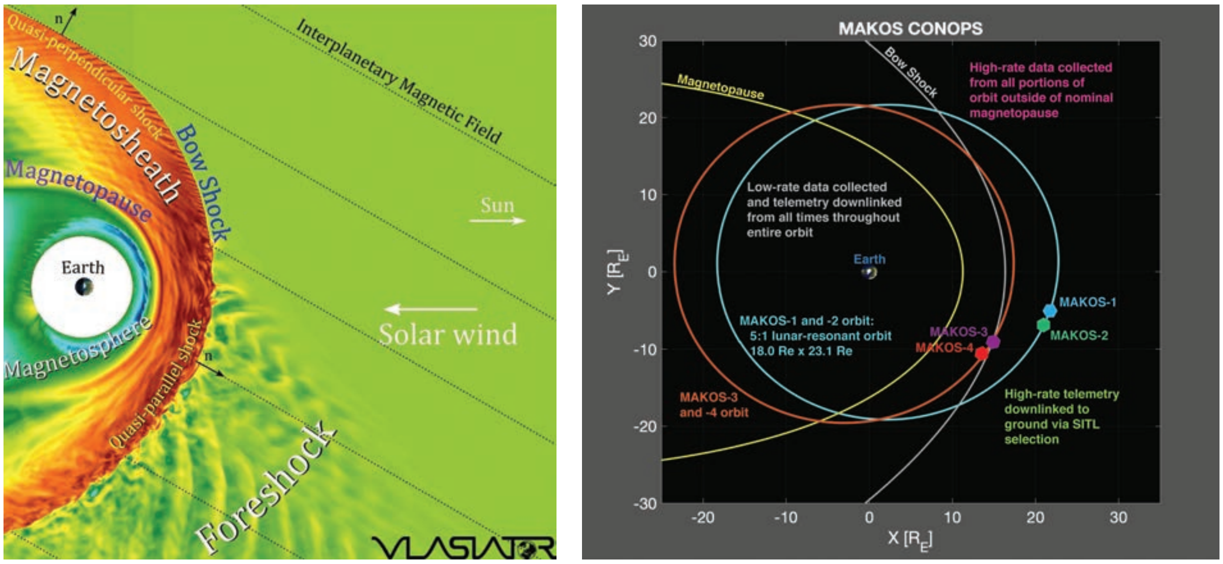

FIGURE C-10 (*Left*) The regions to be explored by MAKOS include the upstream foreshock region, the bow shock, and the magnetosheath. (*Right*) The MAKOS concept uses 4 spacecraft, two upstream and two downstream of the bow shock to explore the physics of collisionless shocks.
SOURCES: (*Left*) Goodrich et al. (2023a), https://baas.aas.org/pub/2023n3i134/release/1. CC BY 4.0; (*Right*) Goodrich et al. (2023b), https://baas.aas.org/pub/2023n3i135/release/1. CC BY 4.0.

only scratched the surface of enabling comparative magnetospheric studies. At the other systems beyond Earth, large regions, populations, and/or processes remain wholly unexplored by previous planetary science missions.

Several community input papers focused on questions surrounding the particle origins, acceleration processes, and losses in the Jovian radiation belts, which are the most intense in the solar system, but remain largely unexplored. Jupiter is a natural stepping stone beyond Earth because it boasts the strongest magnetic field; largest magnetosphere; the most active moon, Io, which is the primary plasma source for the system; the fastest rotation; and the most powerful aurora and radiation belts. Additionally, Jupiter's environment continually exhibits extreme regimes that cannot be emulated even during the most extreme geomagnetic storms at Earth. Heavy ions in the heart of the Jovian radiation belts reveal a local source of >50 MeV/nucleon oxygen, a phenomenon that does not occur at Earth but may be analogous to stellar or astrophysical acceleration processes. The Comprehensive Observations of Magnetospheric Particle Acceleration, Sources, and Sinks at Jupiter (COMPASS at Jupiter) mission concept is designed to investigate these questions.

COMPASS aims to make significant progress toward understanding the distinctive and universal processes at play across complex space environments by focusing on the Jovian system where the large, material-laden magnetosphere with active moons hosts numerous processes that simultaneously facilitate in the production, but also sculpt losses in particle distributions. Figure C-11 illustrates many of these processes. COMPASS will aim to understand how particle origins, acceleration, and loss processes compete across a multidimensional parameter space that includes space, time, energy, composition, and charge state. To do this, the COMPASS mission will address four science goals: (1) discover how moon and ring material in the Jovian space environment contribute to the radiation belts, (2) reveal additional particle sources of the Jovian radiation belts, (3) discover how Jupiter accelerates charged particles to such exceptionally high energies, and (4) reveal the loss processes of energetic charged particles in Jupiter's magnetosphere and resulting X-ray emissions. The Jovian magnetosphere is laden with ions sourced by its geologically active moons, although major questions remain regarding the ultimate origin of the heavy ions—that is, whether they come primarily from Io or Europa. Furthermore, observational evidence suggests that the aurora, solar wind, and/or atmosphere may also provide significant particles to the radiation belts. Acceleration processes found at Earth, such as radial transport and wave–particle interactions, are also known

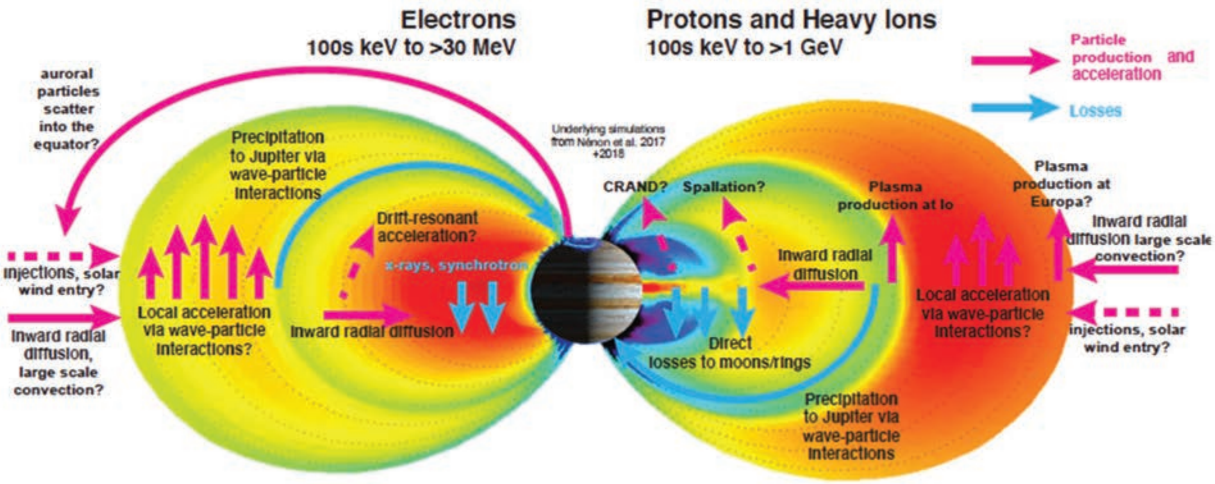

FIGURE C-11 Illustration of the dynamic processes thought to occur at Jupiter that lead to the intense radiation belts observed there. SOURCES: Clark et al. (2023), https://baas.aas.org/pub/2023n3i067/release/1. CC BY 4.0; Modified from Nénon et al. (2017, 2018).

to occur at Jupiter, although their relative impacts on the overall system may differ. The fact that Jupiter's magnetosphere greatly exceeds the energies and intensities found in any other planetary environment despite its high density of neutrals that absorb and cool charged particles remains one of the largest mysteries in planetary magnetospheres. Balancing losses with acceleration and source processes is critical for establishing and sustaining robust planetary radiation belts. Jupiter, like Earth, loses particles via precipitation to the atmosphere, but unlike Earth the magnetopause is too far away (60–100 R_J) to impact the radiation belts. Therefore, losses in the inner magnetosphere, such as WPIs near Io and resulting scattering into the atmospheric loss cone and direct absorption by inner moons, are likely the critical factors in sculpting the radiation belt particle distributions.

COMPASS will achieve this using a single solar powered spacecraft on a 5.5-year interplanetary trajectory to Jupiter that leverages a deep space propulsive maneuver and an Earth gravity assist. Upon arriving at Jupiter, the COMPASS mission is broken into two science phases over the nominal ~1.5-year mission. During Phase I, the COMPASS spacecraft moves into a high-inclination (~50°) orbit with perijove near Io's orbital distance (5.9 R_J), which is critical for investigating particle origins and losses science objectives via X-ray imaging. During Phase I, the mission leverages several flybys of Io to reduce the orbital period and slowly move the apojove in from >200 R_J to ~60 R_J; it then uses a series of Callisto flybys to simultaneously reduce inclination (to ~25°) and perijove altitude (to <2 R_J). During Phase II, at low (≤15°) inclination with periapsis ~1.3 R_J, the spacecraft will make several deep dives into the most intense radiation environment to obtain the first in situ measurements of the near-equatorial radiation belt and synchrotron regions.

COMPASS carries a comprehensive space physics payload of ten instruments. The particle instrument complement includes two thermal plasma detectors (~10 eV/Q to ~10 keV/Q), a suprathermal particle detector (few keV/Q to 100s keV/Q including mass and charge-state compositions), an energetic particle detector (10s keV to > few MeV), a relativistic particle detector (~1 to 10s of MeV), and an ultra-relativistic particle detector (~10 to 10,000s MeV/nuc ions and ~8 MeV to > 50 MeV electrons). The fields instruments include a fluxgate magnetometer, a search coil magnetometer, and an electric field waves sensor, each of which can measure the target fields in three dimensions. Last, COMPASS also carries an ~0.5–10 keV X-ray imaging instrument to distinguish soft and hard X-rays.

Despite neither targeting the Sun nor the terrestrial system, COMPASS is appropriate for the STP Program as it will directly addresses multiple STP objectives, such as understanding fundamental physical processes of the space environment at other planets, understanding how the habitability of planets is affected by solar variability and planetary magnetic field, and developing the capability to predict the extreme and dynamic conditions in space.

COMPASS is studying the fundamental science of particle acceleration and loss, making it appropriate for an STP mission. It is exploring a region that has never been explored before, so the maturity level is low. Still, it has aspects of an LWS mission. It is focused on understanding the radiation belts, a known hazard to spacecraft. In this way, it supports preparation for heliospheric exploration to extreme environments.

COMPASS is directly aimed at the Longer-Range Goal on comparative magnetospheres. It will study how Jupiter accelerates charged particles to such exceptionally high energies and how moon and ring materials in the Jovian space environment help create the radiation belts even though they simultaneously limit them. It will further reveal the processes seeding Jupiter's unique, intense radiation belts and the loss processes of relativistic charged particles in Jupiter's magnetosphere and the resulting X-ray emission.

Ground-Based Project: Distributed Network

Multipoint, multi-instrument observations have made crucial contributions to the understanding of 3D ionospheric electrodynamics, but progress has been limited by the reliance on mostly ad hoc combinations of measurements from networks with a wide range of scientific objectives and instrumentation. The Distributed Network Facility would be a paradigm shift toward a coordinated measurement strategy designed to transform the understanding of multiscale, 3D ionospheric electrodynamics. These 28+ platforms would be deployed across North America, as illustrated in Figure C-12, with each platform including red-green-blue ASIs, magnetometers, GNSS receivers, riometers, and high-frequency (HF) sounders.

Most of these instruments are analogous to a system currently being deployed across Canada by Canadian universities with support from CSA, and international collaboration to maximize spatial coverage would be a key aspect of the deployment of the Distributed Network. Little technology development is needed apart from the HF sounder, which would be used to provide an additional diagnostic of ionospheric conductance. This blend of instruments would enable the network to constrain critical state parameters across a wide area, including the traditionally sparsely sampled mid-latitude region in the United States. These parameters, including ionospheric conductance and current, would complement the ionospheric flows provided by SuperDARN to provide a complete specification of the system needed to quantify energy deposition rates for multiscale phenomena. They would

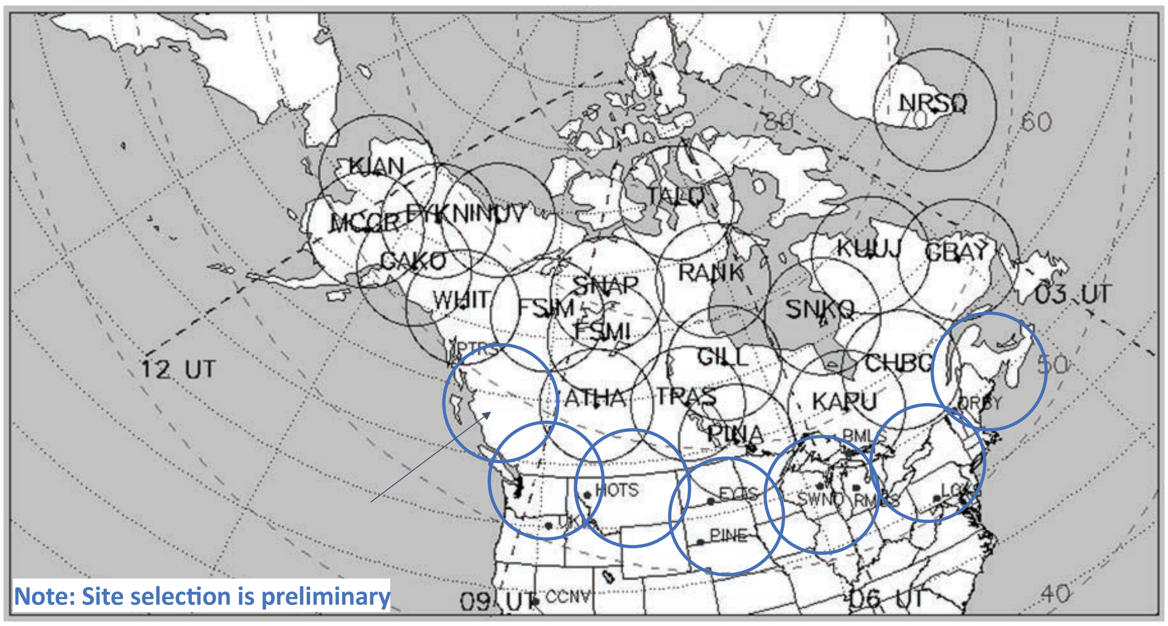

FIGURE C-12 Suggested locations for the 28 stations that would comprise the distributed network. It consists of the sites used for the THEMIS ground-based network and seven new mid-latitude stations.
SOURCE: Based on S.B. Mende, S.E. Harris, H.U. Frey, et al., 2008, "The THEMIS Array of Ground-Based Observatories for the Study of Auroral Substorms," *Space Science Reviews* 141(1–4):357, https://doi.org/10.1007/s11214-008-9380-x, Springer Nature.

also complement AMPERE, sampling smaller spatial scales and shorter temporal scales but over a more limited area. They would also provide the conductance measurements—validated against co-located IS radar conductance measurements—needed to understand how the magnetosphere responds to changes in the ionosphere. Last, the measurements provided by the Distributed Network in the northern United States would be a game changer in terms of understanding the unique electrodynamic coupling processes that occur during extreme events. Despite much of the northern United States being a high-hazard region for geomagnetically induced currents, and despite numerous studies showing that the auroral oval dips into the United States during moderate and extreme storms, this region is sparsely covered by most of the instruments contained in the distributed network platform, including ASIs. The Distributed Network would also have the ability to redeploy some platforms to address new science objectives or fill spatial gaps left by other projects should they arise.

The Distributed Network of 28+ platforms would be Mid-scale Research Infrastructure (MSRI), most likely in the MSRI-2 category; there would be the possibility to identify efficiencies in deployment and operations through, for example, international collaborations.

The Distributed Network would predominantly address PSGs 1 and 3. For Goal 1, it would provide multiscale information about auroral structures, ionospheric current systems and flows, and particle injections/precipitation across a wide area. For Goal 3, it would provide a complete set of ionospheric parameters, including the critical conductance parameters, across a wide area. The network would also enable continuous space and time coverage of high- and mid-latitude regions needed to maximize the science return from several upcoming and proposed satellite missions. Studies of energy deposition and I-T dynamics using GDC mission measurements could exploit the Distributed Network's ability to continuously monitor multiscale ionosphere phenomena and resolve ambiguities related to temporal/spatial variations observed by GDC. The OHMIC mission would benefit from ASIs providing observations of meso-scale processes related to acceleration regions and networks of GNSS receivers showing the ionospheric impact of auroral processes, making the Distributed Network relevant to PSG 2. As another example, the multiscale specification of ionospheric state parameters in 2D, combined with the multipoint in situ measurements of magnetospheric processes provided by Links, would transform the understanding of how ionospheric processes impact the magnetosphere and vice versa.

Last, in addition to the PSGs discussed in this section, the Distributed Network also provides measurements of several parameters needed for a range of I-T investigations (e.g., TEC and conductance) and for space weather monitoring and data assimilation (e.g., geomagnetic disturbance and TEC).

Ground-Based Project: SuperDARN Network

SuperDARN provides multiscale measurements of 1D and 2D ionospheric flows in both the northern and southern hemispheres. By providing measurements of both steady and rapidly varying flows and electric fields, this network of radars provides crucial information needed to quantify the relative importance of electric field variations with different spatial and temporal scales for overall energy deposition rates. Working together with the Distributed Network and satellite missions such as Links, studies using the existing SuperDARN network can also identify the causes of ionospheric electric field variations and their effect on multiscale energy dissipation on the M-I system.

The panel endorses continued support for operations at existing U.S.-led radars (MSRI-1) when the current NSF grant expires and continued U.S. participation in the international SuperDARN consortium. In addition, the panel endorses NSF support to upgrade the hardware and software to improve 2D imaging capabilities for individual radars. The upgraded SuperDARN imaging capabilities would further improve the ability to remote sense mesoscale flow variations needed to assess local and global impacts of mesoscale disturbances and track energy flow through the M-I system. Last, SuperDARN provides global measurements that by themselves, or assimilated into global convection maps, provide crucial information about north-south and east-west asymmetries in the coupled M-I system. These asymmetries are known to significantly affect, and be affected by, M-I coupling processes.

The continued operation and upgrades to SuperDARN would predominantly affect PSGs 1 and 3. SuperDARN measurements will continue to play an essential role in monitoring global electrodynamic coupling processes. For example, the SuperDARN convection maps are assimilated into global simulations that require measurements in both hemispheres to realistically capture M-I current systems during asymmetric solar wind driving conditions.

In addition, SuperDARN provides ionospheric flow measurements and related global convection patterns that are used for a range of ITM investigations and for space weather monitoring.

Ground-Based Projects: PFISR/RISR Incoherent Scatter Radars

The Advanced Modular Incoherent Scatter Radar (AMISR) network includes three faces: PFISR at Poker Flat, Alaska and RISR-North and RISR-C at Resolute Bay, Canada. PFISR and RISR-North are owned by NSF, while RISR-C is owned by the University of Calgary. IS radars provide comprehensive ionospheric plasma parameter measurements, including line-of-sight plasma flows and thus convection, plasma temperature, density, and other derived parameters, such as composition and neutral wind profiles. IS radars are valuable for fundamental magnetosphere–ionosphere–thermosphere–mesosphere (M-I-T-M) coupling science through continuous observations of comprehensive ionospheric plasma parameters at various latitudes, providing key information about the energy deposition rate to the I-T system, conductivity, and initiation of ion outflow. They also remotely sense dynamics and key features in the magnetosphere. More specifically, located deep in the polar cap, RISR-N measures polar cap ionosphere density structures, convection, and cusp reconnection rate during northward interplanetary magnetic field (IMF). On the other hand, PFISR measures the subauroral and auroral ionosphere routinely, and measures cusp dynamics during strong southward IMF.

Both NSF AMISR faces have been operating for more than a decade and require complete refurbishment of antenna elements to bring back full capacity. Continuous support of the AMISR network (MSRI-2) is required to ensure long-term operation. Their field-of-view overlaps with the proposed Distributed Network, and so their measurements can be used to validate the Distributed Network observations, including the conductance obtained from the new HF sounder technique. They also both extend the network measurements to 3D and complement their measurements in parameter space.

IS radar measurements are directly relevant to PSGs 1, 2, and 3. IS radars can measure the convection electric field and electron density and temperatures, which can then be used to calculate the conductivity and the energy deposition rate from the solar wind-magnetosphere to the I-T system. These energy deposition rates can be estimated across different scales in locations corresponding to different magnetospheric regions depending on the location of IS radars and the geomagnetic activity level. Through their comprehensive measurements, IS radars can reveal where and how the ionospheric plasmas are extracted from the ionosphere into the magnetosphere. The ionospheric upflow can be produced by frictional heating of the ions and/or enhanced ambipolar electric field owing to electron heating, parameters measured by the IS radars. Therefore, IS radars are essential ground-based instruments for understanding the energy and mass transfer between the M-I-T-M system.

More specifically, IS radars can contribute to planned and proposed magnetosphere missions, space weather studies, and other solar and space physics disciplines, such as I-T-M. IS radars provide ionospheric measurements from the subauroral zone to the polar cap and remotely sense aspects of magnetospheric dynamics such as fast convection flow channels, which are directly relevant to the Links and OHMIC missions concepts. IS radars also provide the location, characteristics, and initiation mechanism of ion upflow, complementing the SOURCE satellite measurements. The conjunction of existing missions, such as DMSP, Van Allen Probes, THEMIS and MMS, with IS radars have provided unprecedented opportunities for enhancing the M-I-T-M system science return. IS radar also frequently provide critical and/or supplementary observations for sounding rocket missions targeting M-I coupling processes. The continuous observations of comprehensive ionospheric plasma parameters from IS radars also provide a key long-term data set for model verification and trend identifications. Regarding space weather, IS radars altitude profiles of plasma density provide key information for understanding their role in the production of radio wave scintillation, including GNSS.

Ground-Based Project: AMPERE-NEXT

AMPERE is a unique program that has been providing important FAC observations of the high-latitude M-I-T-M coupling region since 2010. It utilizes the magnetometer measurements onboard the Iridium satellite constellation and is an excellent example of collaboration between a government agency and private space industry. AMPERE (MSRI-1) has been incredibly valuable for fundamental M-I-T-M coupling science through direct, continuous observations of global FAC systems, providing key contextual observations for other spacecraft and ground-based assets, and being used in empirical models and physics-based simulations of the I-T system as high-latitude electrodynamic drivers and for validation.

AMPERE-NEXT became available in 2022 and provides up to 10 times higher attitude accuracy, approximately 2 times lower error in δB, and over twice the sampling cadence per spacecraft than data from the Iridium Block-1 constellation originally used for AMPERE.

In the next decade, robust investment in ground-processing infrastructure and operations support is required to enable AMPERE to become a valued resource for now-casting and system-state determination. With ever increasing LEO satellite constellations, the AMPERE program has the potential to be expanded to incorporate additional constellation data streams with either data from Iridium NEXT and future Iridium satellites or other LEO satellites or constellations to increase the temporal and spatial resolutions of FAC measurements. In addition, opportunities need to be explored for hosted payloads consisting of smaller, low-cost sensors that provide a more complete picture of global electrodynamics, such as precipitating particles and plasma convection measurements, on the satellites generating the AMPERE data stream.

The AMPERE-NEXT measurements are directly relevant to PSGs 1, 2, and 3. The AMPERE measurements reveal how global 2D FACs evolve in response to changing solar wind–magnetosphere–ionosphere conditions, including north–south and dawn–dusk asymmetries. They provide global contextual information in the regions where ionospheric upflow and outflow are initiated. Combined with other measurements, such as the SuperDARN convection, they could also be used to determine how global DC Poynting flux evolves in response to changing solar wind and magnetosphere conditions.

More specifically, AMPERE-NEXT can contribute to planned and proposed magnetospheric missions, space weather studies, and other solar and space physics disciplines, such as ITM. The coordination of existing missions with AMPERE, such as DMSP and TIMED, has demonstrated opportunities for enhanced science return. In the future, AMPERE can provide 2D global context in both hemispheres, including mesoscales in the latitudinal direction, for three magnetospheric mission concepts (e.g., Links, OHMIC, and SOURCE). It also provides an additional diagnostic of energy input related to ionospheric upflow and outflow for the SOURCE mission concept. In terms of contribution to space weather studies, AMPERE FACs have already been incorporated into global I-T models as high-latitude drivers and AMPERE has the potential to provide critical contributions to space weather operations and space domain awareness.

Ground-Based Project: Mid-latitude Incoherent Scatter Radar

Multiple community input papers recommended expanding midlatitude and subauroral science capabilities in upcoming observation systems. The mid-latitude I-T region maps to the inner magnetosphere, where the hot and cold plasma interface is located, and thus remotely senses dynamics in the inner magnetosphere. Compelling science phenomena, such as subauroral polarization stream (SAPS), STEVE emission, and storm-enhanced density, occur in this region. A mid-latitude IS radar (MSRI-2) would provide measurements of the subauroral and auroral convection flows and other plasma properties in this region. During strong solar wind driving conditions, IS radar measurements combined with spacecraft measurements at higher altitudes could be used to understand the initiation conditions of ion upflow and outflow.

Similar to AMISRs, the mid-latitude radar is directly relevant to PSGs 1, 2, and 3, and will be able to remote sense magnetospheric dynamics and provide ionosphere-to-magnetosphere convection comparison for magnetospheric missions (e.g., Links, SOURCE, OHMIC). The mid-latitude IS radar field-of-view needs to overlap with that of the Distributed Network and would complement and expand their measurements in parameter space. The temporal and spatial resolution of ionospheric measurements need to be improved either through innovative improvement of an existing facility or through building a new phased-array mid-latitude radar.

Projects That Need New Technology Development

Magnetosphere–Ionosphere Observatory (MIO): A major objective of PSGs 1 and 3 is to determine the connection between multiscale structures in the plasma sheet and the discrete structures in the aurora. While the Links mission concept will observe both the plasma sheet and the aurora, the actual connection between them will have to be inferred. To definitively determine the link between them requires a technique to actually trace the field line from the plasma sheet to the ionosphere. The Magnetosphere–Ionosphere Observatory (MIO) mission concept is designed to do exactly that. MIO will make measurements directly connecting the magnetosphere to the ionosphere, a key knowledge gap in the understanding of M-I-T-M phenomena. This is achieved by operating a powerful 1 MeV electron accelerator on a primary spacecraft in the equatorial nightside magnetosphere. The beam is directed into the atmospheric loss cone and deposits the energy of ionizing electrons into the atmosphere to optically illuminate the magnetic footpoint of the spacecraft. An associated network of ground-based imagers in Alaska and Canada will locate the optical beamspot to unambiguously establish the connection between equatorial magnetospheric measurements and ionospheric phenomena. The equatorial magnetospheric measurements are made by four nearby daughter spacecraft that are used to identify magnetospheric regions, boundaries, and generator mechanisms, enabling the magnetospheric drivers of various aurora, ionospheric phenomena, and FACs to be determined.

"Magnetosphere-to-Ionosphere Field-Line Tracing Technology" using an energetic electron beam fired from a magnetospheric spacecraft was listed in the 2013 decadal survey as an "instrument development need and emerging technology" that (a) is in need of a technology boost and that (b) could have a substantial impact in solar and space physics. There is still a need in the coming decade to further develop high-power (~kW) energetic electron beam (~1 MeV) technology so that mission concepts that utilize it can be realized.

Dropper/dipper probes: The altitude range from ~80 to ~160 km—that is, the D- and E-regions of the ionosphere—is a critical region where key aspects of the energy and momentum transport between the M-I-T system take place. This region is immensely important because it is the altitudinal crossroads where ionospheric electrodynamics (e.g., Joule heating and current closure) occur in concert with significant neutral densities and thermospheric processes (e.g., neutral winds). Unfortunately, despite the importance of this region in understanding the intricacies of the coupled near-Earth space system, it still remains woefully underexplored with most focused investigations coming from the sounding rocket program. The paucity of measurements in this region stems from the general inability to investigate these altitudes using orbital spacecraft owing to substantial atmospheric drag that arises from the combination of required high orbital velocities and relatively large plasma and neutral densities at altitudes below ~400 km. While previous LEO missions have provided information on the magnetospheric input into the upper atmosphere and ionosphere—as well as preliminary insight into its response—these missions have been unable to probe the mechanisms of coupling. Although concepts for orbital "dipper" missions that regularly dip into very low Earth orbit (VLEO; i.e., the E-region ionosphere) have been circulating in the community for several decades, no such mission has been developed in the United States; the Daedalus mission formulated—but not implemented—by ESA was to follow a similar approach.

Over the next decade, the community would benefit from further development of the "dipper" architecture—that is, repeatedly descending into this region and then using propulsion to regain altitude—and/or explore the feasibility and technology necessary for deployable (and expendable) low-resource "dropper" probes that can deorbit to explore these very low altitude regions.

Low SWaP capable instruments: Two conditions are emerging that rely on low-SWaP instruments and provide significant opportunities. First, as the understanding of the magnetosphere matures, the community requires more measurements to constrain the conceptual understanding and models. One way to enable this continued growth is through lowering the SWaP of instruments to permit more complex instrument suites to be flown simultaneously on a single platform or with the same hosting resources. Second, the number of spacecraft being launched has steadily grown over the past several years and is projected to rapidly expand over the next decade. Much of the expansion is occurring in the commercial and defense sectors, which are growing through single-spacecraft missions but also through constellations with hundreds and even thousands of spacecraft. Opportunities have begun to emerge to fly hosted payloads, placing science-based instruments on commercial spacecraft. Such opportunities are expected to continue and grow. These opportunities often come with low-SWaP resource accommodations. Investing in developing novel low-SWaP instruments as well as reducing the resources required for current instrumentation while maintaining performance is expected to enable major science discovery in the next decade through participation in such rideshare opportunities.

C.5.3 Opportunities for Collaboration

Collaborations Between NASA and NOAA

Upgraded L1 Solar Wind Monitor

As global-MHD, radiation belt, and other magnetospheric models become more accurate, an ultimate test for each one is to represent realistic, complex relevant intervals such as storms, substorms, and smaller events. Accurate, high-resolution, and continuous measurements of the solar wind velocity and density and of the IMF from L1 are essential in representing the solar wind state as it couples to the magnetospheric state. In addition, NOAA and DoD use several magnetospheric models operationally, so continuous monitoring of the solar wind is a needed capability for space weather forecasts.

NOAA, in close collaboration with NASA, is planning to replace operational data sets from the Solar and Heliospheric Observatory (SOHO), Advanced Composition Explorer (ACE), and Deep Space Climate Observatory (DSCOVR) missions, which are all expected to reach the end of their life in the mid-2020s. NOAA's Space Weather Follow On (SWFO) program features the SWFO-Lagrange 1 (SWFO-L1) observatory planned to launch in 2025 with state-of-the-art instruments, including plasma, suprathermal particle, and magnetic field sensors, as well as a coronagraph to provide continuity from SOHO. An additional SWFO coronagraph was onboard the GOES-19 satellite, which launched in June 2024; its first images were returned in September 2024. These data sets will be useful for monitoring the solar wind in real time and for improving physical and empirical models of solar wind- magnetosphere coupling.

In coming years, magnetospheric models will need additional detail of the heliospheric input such as orientation and curvature of solar wind fronts. This will require multiple solar wind and IMF data sets from L1, currently provided by ACE, DSCOVR, and Wind, and in the near-term by SWFO-L1, IMAP, and other missions. To provide this critical input to the magnetosphere, it is important that NASA and NOAA collaborate to optimize spatial coverage of solar wind fronts with orbits around L1.

Magnetospheric Particle and Field Measurements

Particle and field measurements are essential diagnostics of magnetospheric processes. Particle flux data are needed to constrain inner magnetospheric models of the radiation belts, ring current and low-energy populations, and for understanding particle acceleration, transport, and loss. Magnetic field data are needed for understanding the field configuration at key locations (e.g., GEO, LEO, and ground) and throughout the system. Electric field measurements are also needed in understanding acceleration and transport at the magnetotail and the ionospheric boundary. The collaborative projects discussed below are organized by observational location.

GEO: Particle and magnetic-field measurements made at the GEO are a key data set for studies of the outer-belt acceleration and transport. In earlier decades, NOAA GOES East and West and DOE LANL spacecraft have provided reference measurements useful for the development and validation of physical and empirical models (e.g., Versatile Electron Radiation Belt [VERB], Comprehensive Inner Magnetosphere–Ionosphere [CIMI], and Relativistic Electron Forecast Model [REFM]). In order to have context for WPIs and other effects in the outer radiation belt, it is important to have comprehensive energy and pitch-angle coverage on a continuous basis, so that events of a wide range of activity levels can be studied. Similarly, in order to understand the magnetic field configuration in the inner magnetosphere it is important to have multiple simultaneous measurements with at least four spacecraft at GEO.

NOAA's current GOES-R series launched its final satellite, GOES-19, in June 2024; it has an expected lifetime of 10 years. The GOES-R series will be followed up with geostationary satellites of NOAA's Office of Space Weather Observations (SWO), which are planned to have similar spatial (East, West) coverage. These measurements will be useful in the development and validation of particle-acceleration models.

To properly understand particle transport and geomagnetic field configuration, studies typically combine GEO data with measurements from other longitudes at GEO as well as other altitudes (i.e., L-shells). GEO particle flux data sets from other longitudes are available from data exchange projects with the Japan Meteorological Agency

(JMA) and Korea Meteorological Agency (KMA) providing flux data from the Himawari and Korean Multi-Purpose Satellite (KOMPSAT) series of satellites, respectively.

LEO: Particle precipitation is an important loss mechanism as well as an M-I coupling process. For understanding precipitation scenarios such as interaction with VLF waves, it is important to include LEO particle data in model development and data analysis. Historically, such data are available from operational missions (DMSP, POES, MetOp).

Coordination between NASA and NOAA for future missions will maximize science return. The NASA GDC mission is planning for low-energy particle (<30 keV for electrons, <40 keV for ions) coverage. NASA's Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC) mission is a companion to GDC for which NOAA has expressed interest in contributing an instrument. Beyond the 2-year nominal duration of GDC and DYNAMIC, it would be valuable to have a long-term observational capability provided by NOAA in coordination with NASA.

Other magnetospheric regions: Progress in understanding acceleration and transport in the inner magnetosphere and elsewhere has relied on a wealth of data from missions that sample the 3D magnetosphere beyond GEO or LEO. Geotail, Cluster, THEMIS, Van Allen Probes, and many other missions have contributed to these data.

In the future, the community would benefit from a full contingent of particle and field measurements from reference locations that complement GEO and LEO. Monitoring the heart of the radiation belts at L~4 would require at least two spacecraft either at geosynchronous transfer orbit (GTO) or MEO. NOAA has plans for an auroral observation capability (see the next section); if that monitoring mission is manifested in HEO, a particle and field sensor payload will be useful in developing and validating models of high-latitude regions including the cusp.

Auroral Imagery

UV and VIS auroral images yield precise quantitative information for M-I coupling, including auroral emission intensity, auroral boundary location and auroral zone area, and precipitation energy deposition, from which the open/closed boundary location and other parameters can be inferred. Missions such as NASA's Polar and DoD's DMSP have provided valuable observations of auroral variability during substorms and other convection events. Most spacecraft data, however, have extended temporal and/or spatial gaps owing to their orbits that pose limitations to quantitative modeling. For modern representations of the coupling, it will be important to have uninterrupted, long-term imagery for event-based and statistical studies.

NOAA goals include a continuous auroral imagery capability either from HEO or LEO, in partnership with other U.S. and international agencies. The emphasis is to initially cover the northern hemisphere down to approximately 60° geomagnetic latitude, assuming conjugacy for modeling purposes; and at a later stage, extending the coverage to both hemispheres. The combination of auroral imaging with ground-based observations of small-scale (~200 km) activity (ASIs, riometers, magnetometers, etc.) as part of a collaboration with international organizations (e.g., CSA and Finnish Meteorological Institute) will provide useful constraints to theoretical models. Having continuous auroral imaging provided by NOAA would simplify many of the missions being considered to study M-I coupling.

Collaborations on Ground Magnetometer Arrays

Geomagnetic manifestations of magnetospheric events are measured by ground magnetometers. Multipoint DC measurements are used for surveys, event remote sensing and timing, and large-scale modeling of geomagnetic disturbances. Ultra-low frequency (ULF) data are used to model and represent field-line resonance growth and damping, M-I coupling, and substorm onset. In the past 2 decades, NSF and the U.S. Geological Survey (USGS) have funded several expansions of the magnetometer network that currently includes most of the continental United States. Through collaborations with CSA and Natural Resources Canada (NRCan), this work covers all of Canada. Progress in this field has enabled space weather nowcasting and related applications at NOAA.

Expanded and continuous ground magnetometer coverage would support geospace missions (e.g., Links) and particularly PSGs 1 and 3. This capability will be the basis for geomagnetic and geoelectric models and related physical modeling and data science, and support space weather nowcasting.

Coordination Between NSF and NASA

Many NASA sounding rocket missions are supported by NSF-sponsored, ground-based assets. Most notably, launches from Poker Flat Research Range in Alaska very frequently coordinate with PFISR for special operations—commonly using specific beam configurations—that are tailored to best suit the target science. Similar coordination occurs with the SuperDARN radar for launches out of NASA Wallops Flight Facility in Virginia.

As discussed above, use of NSF-sponsored assets in conjunction with NASA missions can greatly enhance the science return. PSGs 1, 2, and 3 are all best addressed with a combination of satellite and ground-based measurements. Although the ground-based facilities would be supported by NSF and the satellite missions by NASA, coordination would ensure, for example, that the Links mission and the Distributed Network are both operational at the same time. It is best if teams designing and operating ground-based assets work closely with satellite teams early in the planning stages of each mission (if ground-based measurements are needed) to make sure ground-based assets will be deployed to the appropriate locations and measure the appropriate parameters for each mission's objectives. There are several ways that NASA and/or NSF could facilitate this, including through funding opportunities that support OSSEs involving both space and ground assets or requiring a portion of the NASA mission team to be devoted to coordination with ground-based instrument operators. This early coordination would enable transformational advances in the next 10 years that address outstanding system science questions.

Collaboration with Planetary Division on Uranus Mission

Multiple community input papers presented magnetospheric and M-I coupling science questions at Uranus. These largely echo the recommendation from the 2013 decadal survey, which recommended that "NASA's Heliophysics Division partner with the Planetary Division to ensure that appropriate magnetospheric instrumentation be fielded on missions to other planets. In particular, the [Solar Wind–Magnetosphere Interactions] SWMI panel's highest priority in planetary magnetospheres is a mission to orbit Uranus." The Uranian magnetosphere presents one of the most unique magnetospheres in the solar system. With the planetary rotation axis tilted by 98 degrees relative to the ecliptic and a highly tilted magnetic field axis (~59 degrees), the orientation of the magnetic field presents an asymmetrical obstacle to the impinging solar wind that varies dramatically on diurnal and seasonal timescales. Also very little is known about Uranus's coupling to the solar wind; it remains unclear whether magnetic reconnection plays an important role in the global magnetospheric dynamics. Meanwhile, the Uranian bow shock enables study of much higher Mach numbers than available at Earth's. The limited observations from Voyager 2 make it difficult to understand the transport mechanisms in Uranus's complex magnetospheric configuration. Because Uranus is a fast (17 hour) rotator and the magnetosphere changes between being open and closed to the solar wind throughout a Uranian day, planetary rotation must play some role in driving plasma flow. Unlike other planets, Uranus's corotational electric field can seasonally become perpendicular to the convection electric field. This unique magnetospheric configuration can serve as a prime laboratory in which to generally understand plasma flows in a magnetosphere because it is difficult to disentangle processes at other planets, such as whether flows result from tail reconnection or centrifugally driven interchange instabilities. Uranus also challenges the understanding of radiation belt physics because it has electron radiation belts that are similar in intensity up to MeV energies as those of Earth and Jupiter, despite having a sparse magnetospheric source population of low-energy plasma, slow acceleration through radial diffusion, and the strongest whistler-mode hiss and chorus waves observed in the outer solar system by Voyager. Last, the coupling of the Uranian magnetosphere to its atmosphere is also complicated and poorly understood, especially given multiple curiosities regarding the planet's difficult to track auroral emissions and unexpectedly low atmospheric temperatures. To address this science, the inclusion of a comprehensive particles and fields payload complement with the necessary resource allocations for magnetospheric investigations is needed on any future planetary science mission to Uranus. The recent *Origins, Worlds, and Life* decadal survey highlighted a Uranus Orbiter and Probe mission as the highest-priority large-scale strategic mission for the next decade. Ensuring robust magnetospheric investigations at Uranus—likely through collaboration between the NASA Heliophysics and Planetary Science Divisions (e.g., see examples summarized in Section C.3, "Longer-Range Goal")—would provide detailed physical insight into multiple global magnetospheric processes of relevance to both the planetary science and space physics communities.

International Collaboration on Ground-Based Projects

There are several international collaborations that could be leveraged in this research program. Several aspects of the ground-based Distributed Network that would enhance the science return of Links and other current and future missions and projects has been, is, or may be supported by the CSA. They have supported several versions of an all-sky camera network across Canada, both as a partner to a NASA mission (e.g., THEMIS) and as a standalone venture. Canada has also supported a network of riometers and magnetometers, which also enhances the science return of current and future missions and projects. Growing this relationship would support the best science return possible. Joint funding opportunities with CSA, NRCan, and others, such as the joint funding mechanism between NSF and the United Kingdom Natural Environment Research Council (NERC) would facilitate this activity. It would also be beneficial to leverage international partnerships to extend the Distributed Network to include coverage in Greenland and other areas so that a wider range of M-I dynamics sampled by Links and other missions and projects are captured. This would also better constrain global conductance, auroral precipitation, and other parameters to more comprehensively address PSGs 1 and 3.

International collaborations continue to be a core part of several other ground-based facilities mentioned in this section. SuperDARN is an international consortium of which only a portion of the radars are operated by the United States; thus, international collaboration is a core part of the SuperDARN facility and will continue to be in the next 10 years. Likewise, international collaboration involving IS radars operated by other countries provide opportunities for comprehensively addressing several science objectives. For example, EISCAT-3D will provide complementary capabilities to AMISR and will also expand the number of possible conjunctions with missions such as SOURCE.

International Polar Years (IPYs) are focal points for significant international collaborative efforts in support of geoscience and geospace research that happen roughly every 25 years. This includes the third IPY in 1957–1958, also referred to as the International Geophysical Year, which involved several geospace researchers (e.g., Sydney Chapman, James Van Allen, Lloyd Berkner) and led to major discoveries, infrastructure improvements, advances in data sharing (e.g., the World Data Centers), and international agreements for scientific collaboration (e.g., the Antarctic Treaty), all of which continue to impact geospace research today. At the time of this report, plans are currently under way for the fifth IPY in 2032–2033. As was the case in 1957, IPY 5 represents a focal point for major international collaborations and thus an opportunity to advance many of the goals in this report. Prior to IPY 5, it would be advantageous to have the ground-based infrastructure discussed in previous sections in place, as well as joint funding mechanisms listed above that facilitate international collaborations. It would also maximize the science return of future missions such as GDC if they are operational in 2032–2033 given the expected increase in international support for ground-based infrastructure in support of IPY 5, thus opportunities for novel campaigns that go beyond mission objectives.

International Collaborations on Space-Based Missions

SMILE Mission

The Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) is a joint mission between ESA and CAS. SMILE is a single spacecraft mission scheduled to launch in 2025. The mission will observe the solar wind interaction with the magnetosphere with its X-ray and ultraviolet cameras, gathering simultaneous images of the dayside magnetopause, the polar cusps, and the auroral oval. Key observations include measurements of how the magnetopause position evolves with time. SMILE will also host an ion analyzer and a magnetometer to monitor the ions in the solar wind, magnetosheath and magnetosphere while detecting changes in the local magnetic field. The focus of the instrumentation and mission objectives is to understand how energy flows through Earth's magnetosphere on a global scale. SMILE is highlighted as an opportunity for the United States to become involved in a global and system-level solar wind–magnetosphere coupling. Potential collaboration opportunities include scientific and modeling contributions before and after the mission has launched.

Plasma Observatory

Plasma Observatory, an ESA mission selected for a Phase A study, is a seven-spacecraft constellation with one mother spacecraft and six identical daughter spacecraft. The spacecraft are configured as two nested tetrahedra covering the ion and MHD scales. The mother spacecraft includes instruments for a full characterization of the fields and particles, including the ion composition with sub-ion-scale time resolution. The daughter spacecraft carries simple instrumentation: a magnetometer, electric field instrument, ion and electron spectrometers, and an energetic particle instrument. The constellation would fly in an 8×10^{18} R_E, 15° inclination orbit, which has an apogee large enough to allow the spacecraft to make in situ measurements in the foreshock. Scientifically, the mission is motivated by the following objectives: (1) How are particles energized at shocks? (2) How are particles energized during magnetic reconnection? (3) How are particles energized by waves and turbulent fluctuations? (4) How are particles energized in plasma jets? and (5) How are particles energized by a combination of these different processes? Potential collaborations could include hardware contributions, mission planning support, and scientific and modeling contributions before and after the mission has launched.

International Planetary Missions

Comparative magnetospheric studies could significantly benefit from international collaborations by leveraging partnerships and collaborations to systems beyond Earth as has been done at Mercury (MESSENGER and BepiColombo), Jupiter (JUICE and Europa Clipper), and Saturn (Cassini).

Interdisciplinary or System Science Approach

While there are still focused science questions in distinct regions of the magnetosphere that need to be resolved, many of the new breakthroughs in the next decade are expected to come by better understanding of the whole system. For this reason, the PSGs outlined here all involve connections throughout the magnetosphere and two of the mission concepts focus on system science.

Links is intentionally designed to study the magnetosphere as a "system of systems." It will study the links between the solar wind and the dayside magnetosphere, where energy is input to the magnetosphere system. It will then study the links between the plasma sheet in the stretched magnetotail and the radiation belts and ring current in the dipolar inner magnetosphere, learning how the solar wind's energy that was stored in the tail is transferred to the inner magnetosphere across Earth's transition region. Last, it will study the links between the magnetosphere and ionosphere by simultaneously measuring magnetospheric phenomenology with its auroral counterpart. Although the Links mission objectives are driven by magnetospheric science—and require studying it as a system of systems—results are also important for I-T studies. Better understanding the magnetosphere driving (i.e., "forcing") on the ionosphere via precipitation is currently an important focus, and current research has shown how meso-scale flows and aurorae that map from the magnetosphere to the ionosphere have drastic impacts on neutral winds and neutral densities. As previously mentioned, the change in ionospheric conductance thanks to magnetospheric precipitation also feeds back to the magnetosphere. Thus, viewing each silo as part of a system of systems is crucial and is a main emphasis of Links.

SOURCE also provides a system-level approach to determine the distribution of cold ions throughout the magnetosphere. It will follow the cold ion pathway from its origin in the ionosphere to the plasmasphere, and study how transport into the lobes and magnetotail leads to the formation of regions like the plasma sheet, warm plasma cloak, and ring current. It will investigate the input drivers of ionospheric outflow, and the mechanisms responsible for the refilling, erosion, and redistribution of plasmasphere ions. The SOURCE implementation is inherently cross-system and cross-scale, using multiple spacecraft with different orbits and in situ and remote sensing observations to provide a global understanding of this mass coupling and its impact on several regions of the magnetosphere. It will lead to better understanding of the life cycle of core plasma through the magnetosphere including how ion outflows are generated and trapped, and their transport pathways and contributions to hot and cold plasma populations.

Magnetic reconnection and shocks are fundamentally processes that govern the interaction of distinct regions. Earth's bow shock is the boundary between the supersonic solar wind and the magnetosheath. Magnetic reconnection allows connections between the magnetically distinct regions of the magnetosheath and the magnetosphere, and also drives global magnetospheric transport and mediates magnetic connections between the magnetosphere and the ionosphere. As such, magnetic reconnection and shocks play a mediating role between the different systems of the solar wind–magnetosphere–ionosphere system and thus are an important part of the system-level science needed to understand this system.

In addition, the interplay of shocks, reconnection, and turbulence and the global/microscale interactions inherent in them link together multiple plasma subfields which have historically been distinct from each other. As such, solving the overarching science question will require MHD modelers to closely collaborate with kinetic modelers, and also requires a close collaboration between the shock, reconnection, and turbulence communities.

Almost inherently, any study of planetary magnetospheres beyond Earth will be interdisciplinary as it will likely bring the magnetospheric community together with the planetary science (and possibly also the astrophysics) community. Furthermore, even if scientific missions to other systems are designed to target focused science questions, with the proper instrumentation they will likely gain cursory insights into aspects of plasma physics that are of interest to the broad solar and space physics community.

C.5.4 Heliophysics System Observatory

While over the past decade, the Heliophysics System Observatory (HSO) has been adopted by NASA to define its fleet of NASA Heliophysics-funded space missions that operate simultaneously to study the dynamics of the solar system, the panel considers it to be a broader concept, similar to that first introduced in the 2013 decadal survey, that includes the ground-based and space-based facilities from multiple agencies, including NASA, NOAA, DoD, NSF, USGS, as well as international partners that are being used to study magnetospheric systems. There are some aspects of the HSO that are universally agreed to be necessary. An L1 monitor is required for a constant measurement of the incoming solar wind and IMF, the driver of magnetospheric activity. A comprehensive set of ground magnetometer stations have been used for decades to generate indices of magnetic activity, such as AE, Kp, and Dst. But there are many other aspects of the system that have not been characterized as long and are not considered for permanently monitoring the magnetospheric system.

The current high-altitude magnetospheric spacecraft contributions to the HSO are the NASA MMS and THEMIS missions, the ESA Cluster mission, and the Japanese Arase mission. The Cluster mission is only expected to operate until September 2024, which will leave no spacecraft in polar orbit. MMS and THEMIS provide critical fields and waves, plasma, and energetic particle measurements in the near-equatorial plane; however, they are not designed for measuring the inner magnetosphere and its intense radiation belts. Arase has provided a critical inner magnetosphere monitor with radiation belt and ring current measurements that is particularly important since the end of the Van Allen Probes mission in 2019.

The field has lacked global imaging of the auroral oval since the end of Polar operations in 2008. Auroral imaging can be used to measure particle precipitation and magnetic activity. By the time a new imaging spacecraft is launched, at least 2 decades will have passed without this vital information. Ground-based ASIs have taken over some of these measurements, but they can be inhibited by clouds or moonlight, and do not have the comprehensive global coverage that includes the dayside. With the technological improvements since Polar's launch in 1996, new generation imagers will not only reestablish global auroral oval monitor capabilities, but they will also enable new science at higher resolutions than previously provided. Links includes auroral imaging as part of its payload.

Neutral imaging can give another global measurement of magnetospheric activity. The TWINS ENA imagers more recently went offline. As mentioned, they have been used to provide 2D snapshots of the energetic ions in the plasma sheet, providing important context for in situ satellites. Both the Links and the SOURCE missions include neutral imaging instruments to provide this global measurement.

NSF, USGS, the Air Force Office of Scientific Research (AFOSR), and the private sector support a wide range of ground-based instrumentation that, while not part of the facilities mentioned earlier in this report, nevertheless form a vital part of the broader HSO and provide powerful tools for more fully addressing the science questions discussed in previous sections. For example, networks of magnetometers overlap with the regions of interest for the Distributed Network and serve to provide more dense measurements in targeted regions necessary to resolve mesoscale currents and measure geomagnetic disturbances related to geomagnetically induced currents. Each of these networks have their own science questions and there remains a need for targeted science investigations using smaller networks, but measurements collected by these networks could readily be incorporated into higher-level data products generated using the Distributed Network when addressing PSGs 1–4. Indeed, magnetometer data have already been successfully aggregated to generate higher-level data products using the SuperMAG facility, and there are already wider community efforts under way to organize magnetometer networks using a facility model. These efforts would significantly expand the range of phenomena that could be explored with the Distributed Network by increasing spatial resolution and expanding spatial coverage to regions not included in the Distributed Network. As another example, measurements from networks of GNSS receivers supported by a range of organizations are already being aggregated by the Madrigal facility and used to produce global TEC maps of the ionosphere. These receivers will provide a valuable significant increase in the number of TEC observations both inside and outside the region covered by the Distributed Network, thus opening the door to additional science investigations.

These examples share another similarity: both GNSS receivers and magnetometers are frequently deployed by geoscience research groups seeking to address questions unrelated to solar and space physics. For example, GNSS receivers are frequently deployed by the cryosphere research community to study ice sheet dynamics. There are many similar opportunities to expand the HSO by working across disciplines to share data. In some cases, it's also possible to collaborate on scientific investigations of mutual interest to multiple communities. For example, magnetometers are often deployed alongside electrometers by geophysicists for magnetotelluric surveys to obtain ground conductivity information. This information is useful for both geophysics and heliophysics research, for example providing crucial constraints needed for geomagnetically induced current studies and to improve M-I remote sensing methods relying on ground magnetometers.

There are many other examples of ground-based instruments that are a key part of the HSO although not discussed in depth in this report, including ionosondes, LiDARs, electrometers, and VLF receivers. There remains a need to support these types of instruments and others in the next 10 years to address the science questions that are the focus of this report and retain the flexibility to explore other science questions. At the same time, the development of data assimilation techniques that can take advantage of heterogenous data sets from multipoint, multi-instrument measurements would yield further benefits including more accurate specifications of the state of the global geospace system.

There are significant gaps in the ground-based portion of the HSO that are already present and/or expected to be present in the next 10 years. This includes (1) gaps present in the oceans, (2) gaps present on land in other countries, and (3) gaps present owing to logistical bottlenecks in Antarctica (elaborated on in Section C.5.5). First, most space physics measurements are challenging in an ocean environment owing to moving platforms and corrosion. In the past 10 years, efforts to fill these gaps have expanded to include deployments on buoys and drones that operate under water, on the surface, and in the air. If these efforts prove successful at scale, they will yield a dramatic improvement in spatial coverage that would benefit PSGs 1–4. Second, international collaborations are vital for obtaining global coverage of the parameters needed to address PSGs 1–4, with many examples over the past decade and beyond—for example, SuperMAG lower (SML) index, Madrigal global TEC maps, the SuperDARN consortium, THEMIS Ground-Based Observatories. This will remain the case in the next 10 years. However, coverage is unevenly distributed owing to a wide range of challenges, from a lack of local resources to differing policies for sharing data.

The DMSP, which launched its first satellite in 1962, has flown a fleet of LEO Sun-synchronous satellites designed to provide the military with important environmental information and weather prediction. The addition of particle sensors designed to measure ionospheric plasma fluxes, densities, temperatures, drift velocities, and scintillation, as well as a magnetometer, provides DMSP spacecraft with space weather capabilities and data sets for fundamental magnetosphere–ionosphere research. These capabilities have facilitated groundbreaking research for the past 5 decades and the creation of important space weather now and forecasting tools. DoD is planning to cancel DMSP and replace it with at least two new satellite systems expected to be operational between 2024 and 2026 that will have microwave, VIS and IR imaging, as well as an energetic charged particle sensor. However, no other particle or field instruments are planned to be part of the instrument suite in the new systems. The loss of DMSP particle and field data will create a void in the supply of research-grade data for M-I coupling studies that will not be filled by the new spacecraft systems. New I-T-M LEO missions are essential to maintain the flow of relevant data sets for the advancement of M-I coupling.

NOAA's operational POES system offers daily global coverage of the atmosphere and radiation of the near-Earth environment with a system of near-polar LEO satellites. Its instrument suite includes space weather and M-I coupling relevant measurements of energy flux of low-energy protons and electrons and flux of higher-energy particles up to radiation belt energies. The panel notes that current support for processing data from the POES mission is low; in addition, the spacecraft in the Joint Polar Satellite System (JPSS), which succeeded the POES fleet, do not carry any space weather instruments. However, the European Organization for the Exploitation of Meteorological Satellites' (EUMETSAT's) MetOp B and C satellites do carry space environment monitor instruments that will continue POES-like particle measurements up to 2027.

However, there are specific requirements from the National Weather Service for particle measurements at LEO. NOAA is pursuing options to satisfy LEO observational requirements through commercial data buys, partnerships, hostings, or other mechanisms and is planning for a LEO observational capability by the end of the decade.[1] However, planning for that mission has a lower priority than planning for L1 or GEO missions. As discussed above, NOAA is also developing plans for auroral imaging. Two scenarios are being evaluated, for observations from HEO or from LEO. Multispectral UV imagery would provide measurements to map the aurora at high geomagnetic latitudes, determine the auroral boundary, and estimate the auroral energy deposition. Supplemental VIS imagery is another requirement. The UV imaging capability from one or more science missions considered (i.e., Links and SOURCE) could inform operational space weather if provided in near real time.[2] Readiness of operational models is an important condition for each one of the above NOAA objectives to go forward. Data assimilation for radiation belt models with LEO-measured fluxes has been already demonstrated. But the assimilation of auroral imagery is more challenging and will require further investment for a transition from research to operations.

Continued operation of HSO missions with solar wind plasma and IMF measurement capabilities, preferably distributed in both radial distance and heliolongitude, are needed to provide critical observations for predicting upstream conditions at the outer planets. This is achieved by propagating the observations to these non-Earth planets during times of good radial alignment with the observing spacecraft.

C.5.5 New Research Programs and Infrastructure Needed

Data Analysis Programs

The opportunities for data analysis under the NASA Heliophysics Research Program that are not mission-specific are the HSR, Heliophysics Guest Investigators (HGI), and LWS Science programs. While these programs do provide a broad range of opportunities, there are still gaps in what can be funded. The HGI program is limited to operating missions, and as noted above, the only currently operating magnetospheric missions are MMS and THEMIS, plus some CubeSats. While HSR permits analysis of both operating and historic data, it encourages a substantial theory/modeling component to the proposed science. LWS studies can also use any data, but the studies are limited to the Focused Science Topics solicited. Therefore, at present opportunities are limited to propose to NASA for a predominantly data analysis project utilizing a historic data set unless it is on an LWS Focused Science Topic.[3] This represents a major gap in the research opportunity landscape and a significant missed opportunity given the many excellent missions that are no longer operating, but still have underutilized data in regions where no more recent data exists. For example, FAST data in the auroral acceleration region and Van Allen Probes data in the inner magnetosphere provide observations that are still highly relevant to the PSGs.

A second gap is that there is no apparent NASA opportunity that encourages equal analysis of both planetary science and heliophysics data for comparative magnetospheres studies. Because Planetary Science and Heliophysics are separate divisions, with their own opportunities, a joint program would be needed to facilitate these studies. While such studies may not be technically barred from any opportunities, their cross-divisional nature is likely (and has been found) to struggle in competition against projects focusing on science topics more fully within the traditional science purview of one division or another. Planetary science missions with strong heliophysics connections that would be excellent for comparative studies include Juno, JUICE, MAVEN, and BepiColumbo.

[1] This paragraph was updated after release of the report to accurately reflect the status of this approach, as of the time of this report.
[2] This paragraph was modified after release of the report to clarify the potential contribution to operational space weather.
[3] This paragraph was modified after release of the report to accurately reflect HSR proposal requirements.

Theory and Modeling

Making advances in theory and modeling, and effectively utilizing new computational tools will require additional investments in these areas. Unraveling the complex physical processes acting on the colocated and interacting magnetospheric plasma populations requires advanced computational methods to describe and predict the dynamic response of these intricate phenomena to solar wind driving. Advancing magnetospheric research through computational means presents numerous multifaceted challenges and considerations, ranging from the complexity of multiscale plasma models to the financial and human resources required for the theory and code development. These multiscale and multiphysics plasma models encompass vast dynamic ranges and complexity, posing significant challenges both in terms of the computational resources needed and the expertise required for model development. Furthermore, ensuring model reliability and effectiveness over time is an ongoing commitment, which can be costly and labor-intensive.

Integrating AI and ML methods into magnetospheric research opens new avenues for discovery. The community now has access to large data sets from current and historically operating space missions, some spanning over several decades. However, these cutting-edge methods require dedicated resources, such as computational power and expertise in AI and ML. Therefore, as the field continues to evolve, interdisciplinary collaboration and strategic investments will play a pivotal role in pushing the boundaries of magnetospheric research.

Computing Infrastructure

A step-change in computational power, code complexity and corresponding labor costs is required to take the beyond-MHD models—such as global Hall MHD, embedded PIC, global hybrid, Vlasov and multifluid-Maxwell—to the level of resolving cross-scale coupling among the domains of geospace. This is a real possibility with the advent of exascale supercomputing with the first supercomputer, Frontier at Oak Ridge's Leadership Computing Facility, exceeding 10^{18} computations per second. Proper funding and support are critical to harnessing the new supercomputing infrastructure. This entails development of models that are tailored to these heterogeneous architectures, as well as analysis and visualization tools that are able to ingest vastly larger amounts of modeling output volume. These necessary changes will bring about breakthroughs in self-consistent cross-scale modeling of geospace.

Extensive computational resources are also needed to analyze the diverse set of observations from disparate instruments obtained at various locations of the system. A vast amount of data has been produced, most of which is difficult to access, that is stored in individual and separate repositories which often have limited storage capacity and limited computing power and have a wide variety of data formats. These limitations constitute a major impediment for the use of a broad ecosystem of data sets required by the premise of system science. Efficiently analyzing the data requires the ability to access any and all of the available data sets without having to go to each individual data repository and creating a comprehensive data set from a patchwork of individual data sets.

One possible solution may be to create a network of all institutions with publicly available data sets under a standard solar and space physics framework so each institutional site can operate by itself while utilizing data from and sharing data with the entire network. Storing data sets in a cloud gives researchers access to all the subscribing data sets within a unified framework, as well as cloud computing tools which drastically reduces the analysis times of tera- or petabyte data sets through parallel processing. NASA is already developing such a concept with its HelioCloud, a data analysis service based on Pangeo. An expansion of this concept to include all institutions that produce geospace data sets will largely contribute to the applicability of the solar and space physics framework cloud concept to system data analysis.

FAIR (findable, accessible, interoperable, and reproducible) data practices have been developed for common data repositories. Currently, the geospace community is far away from the interoperable and reproducible aspects. New data frameworks would be useful that give users a way to find, access and cite (i.e., using digital object identifiers [DOIs]) various types of data easily, along with descriptive information about the said data products so that it is understood by users who are familiar with the data products but are not experts. This would allow for interoperability of the data products and finally, reproducibility of research results.

NSF Investments in Antarctic Infrastructure

Currently, the NSF U.S. Antarctic Program (USAP) is facing a severe shortage of logistical resources. More than half of the 131 projects and activities funded for 2023–2024 have been canceled owing to lack of logistical support, including reductions in LC-130 aircraft and icebreaker support. Over the next decade, unless NSF/USAP priorities change, most measurements outside the major bases are likely to be eliminated while measurement capabilities at major bases will also likely be degraded. NSF supports infrastructure for several ground-based measurement networks including those located at the permanent bases maintained by the USAP (e.g., South Pole, McMurdo, and Palmer) and autonomous systems distributed across West and East Antarctica. The measurements include several SuperDARN radars, ASIs, magnetometers, and GNSS receivers that are crucial for addressing several high-priority science questions described above; for example, SuperDARN, GNSS TEC, and magnetometer measurements are already assimilated into global geospace models and used to study how north-south hemisphere asymmetries affect global electrodynamic coupling processes. These measurements are also crucial to the ITM and space weather communities; for example, distributed networks of GNSS TEC receivers in Antarctica enable studies of north-south hemisphere asymmetries in polar cap patches, tongues of ionization, and other I-T phenomena, while neutron monitors provide crucial information relevant to space weather nowcasts/forecasts. To mitigate some of these issues, international collaborations could be used to share logistical resources and access regions of Antarctica that are becoming less accessible to USAP. NSF investments in Antarctic Research are particularly important given the rapidly evolving research developments related to north-south hemisphere asymmetries and the growing need for assimilating southern hemisphere measurements in space weather models.

C.6 CONCLUDING REMARKS

The Panel on the Physics of Magnetospheres has presented a comprehensive research strategy to address the PSGs laid out in Sections C.2 and C.3 and take advantage of the emerging opportunities identified in Section C.4. Table C-9 summarized the required measurements and advancements in theory and modeling to achieve the PSGs. The panel has identified missions and ground-based facilities that can be used to address these goals, have identified aspects that need further development, and have identified the myriad opportunities for collaboration between divisions, between agencies and with international partners that would enable significant progress in the field.

Table C-10 summarizes how the identified missions and facilities address the PSGs. These missions represent example implementations that will provide the measurements required to address the goals. The missions included GDC and the Uranus Flagship Collaboration, along with the five new missions. GDC is a critical element of the strategy in the coming decade for addressing PSG 3. Contributions to the Planetary Science Division Uranus mission are a cost-effective way to make immediate progress on the Longer-Range Goal.

As shown in the table, the ground-based facilities make critical contributions to the science goals. They provide a subset of the required measurements, but they do not replace the need for missions. For PSG 1, for example, the ground-based measurements give critical information on the ionospheric link, but they cannot provide the connection to the magnetosphere that will be given by the Links plasma sheet measurements, or the global aurora images provided by the Links imager. For PSG 3, ground-based measurements again provide critical contributions, but in situ measurements from GDC are required to obtain the neutral winds and electromagnetic and kinetic energy inputs to the I-T system and to measures multiscale field-aligned currents using variations in spacecraft spacing. The combination of spacecraft and ground-based measurements provides a powerful set of observations for resolving the dynamic coupling between the ionosphere and the magnetosphere.

In addition, the most important programmatic investments are identified as the following:

- Coordinated multipoint measurements from diverse sources to capture flow throughout the interconnected system.
- Programs that facilitate international collaboration including joint funding opportunities that span multiple countries.
- Inter-agency collaboration among NASA, NSF, NOAA, and DoD to coordinate measurement campaigns that involve multiple missions and/or ground-based facilities.

TABLE C-10 Mapping the Missions and Facilities to the Priority Science Goals

Physics of Magnetospheres	**Priority Science Goal 1**	Objective 1a	Objective 1b	Objective 1c	**Priority Science Goal 2**	Objective 2a	Objective 2b	Objective 2c	Objective 2d	**Priority Science Goal 3**	Objective 3a	Objective 3b	Objective 3c	Objective 3d	**Priority Science Goal 4**	Objective 4a	Objective 4b	Objective 4c	**Longer-Range Goal**	Objective LRa	Objective LRb	Objective LRc
Mission																						
GDC				◐			◐				●	●	●	◐		◐						
Links		●	●	●							●		◐	◐		◐	◐					
SOURCE		◐				●	●	◐	●		◐											
OHMIC							◐				◐	◐		◐								
COMPASS at Jupiter																				●	●	●
MAKOS																◐	●	●				
Uranus Flagship Collaboration																				●	●	●
Facility																						
Distributed Network		●	●	●		◐	◐				●	●	●	●								
SuperDARN Network		●	●	◐							●	◐	◐	◐		◐						
PFISR/RISR		◐	◐	◐			●				●	●	◐	◐		◐						
AMPERE-Next				◐							◐	◐	●									
Mid-latitude ISR						◐	●				●	●		◐								

● *Critical contribution;* ◐ *Important contribution;* (empty) *Minimal/no contribution*

NOTE: Acronyms are defined in Appendix H.

- Expanded opportunities for data analysis from NASA missions no longer in operation, non-NASA missions, or ground-based assets.
- Increased resources for theory and modeling efforts to support utilizing new computational tools, including AI and ML methods, and to support exascale supercomputer architectures.
- Expanded opportunities for the space physics research community to study other planetary magnetospheres and atmospheres—through modeling, theory, and data analysis.
- Cooperation between the NASA Heliophysics Division and Planetary Science Division to ensure that future planetary missions include appropriate space physics instrumentation when feasible.

The panel eagerly looks forward to the implementation of a program addressing many of these goals.

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D

Report of the Panel on the Physics of Ionospheres, Thermospheres, and Mesospheres

D.1 INTRODUCTION

The decadal charter for the Panel on the Physics of Ionospheres, Thermospheres, and Mesospheres (ITM panel) is to identify the highest-priority science goals (PSGs) for the coming decade and develop a compelling research strategy to address those goals that incorporates both ground- and space-based investments, model development, interdisciplinary emerging opportunities, and enabling capabilities needed to lay the groundwork for continued advancement in future decades. Per the ITM panel statement of task, this report assumes that the Geospace Dynamics Constellation (GDC) and Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC) missions will be executed as a prerequisite to the strategic implementations described in this report.

The vision presented in this panel report reflects an overall paradigm shift relative to past reports, which is motivated by a growing recognition that the ionosphere–thermosphere–mesosphere (ITM) is more than just the bridge between the lower atmosphere and magnetosphere. Instead, the ITM represents within geospace the clearest example of physical complexities that require a system science approach to their investigation.

The ITM hosts a myriad of processes encompassing chemical reactions, fluid dynamics, plasma physics, and their coupling, as the atmosphere transitions from a predominantly well-mixed neutral gas to a magnetized plasma. Beginning nearly 100 years ago with the discovery of the Appleton Anomaly and extending to the dramatic ITM response to the 2022 Hunga Tonga–Hunga Ha‘apai volcanic eruption, the community has mostly focused on individual phenomena or state parameter observations to elucidate the underlying ITM processes. Furthermore, the limitations in the technological capabilities, budget resources, and interagency coordination of the past 2 decades drove previous decadal surveys to construct phenomenologically focused goals within individual regions. Although this approach served the community well for that time, the next great step for ITM science is to delve into the intricacies of the processes acting on and within the ITM when viewed as a system. This endeavor requires a transformative system science approach that is reflected in the next decade's science goals and implementation strategies, which are detailed in the sections that follow.

Science theme: Embrace a system perspective as an enabling paradigm for understanding complexity in the ITM and in the geospace system in which the ITM is embedded.

As illustrated in Figure D-1, further advances in ITM science require that the research be conducted within a system science paradigm that emphasizes the complex linkages between different regions, scales, domains, and processes; quantifies the relative significance of competing causal pathways; and establishes the baselines from which emergent behavior can be distinguished.

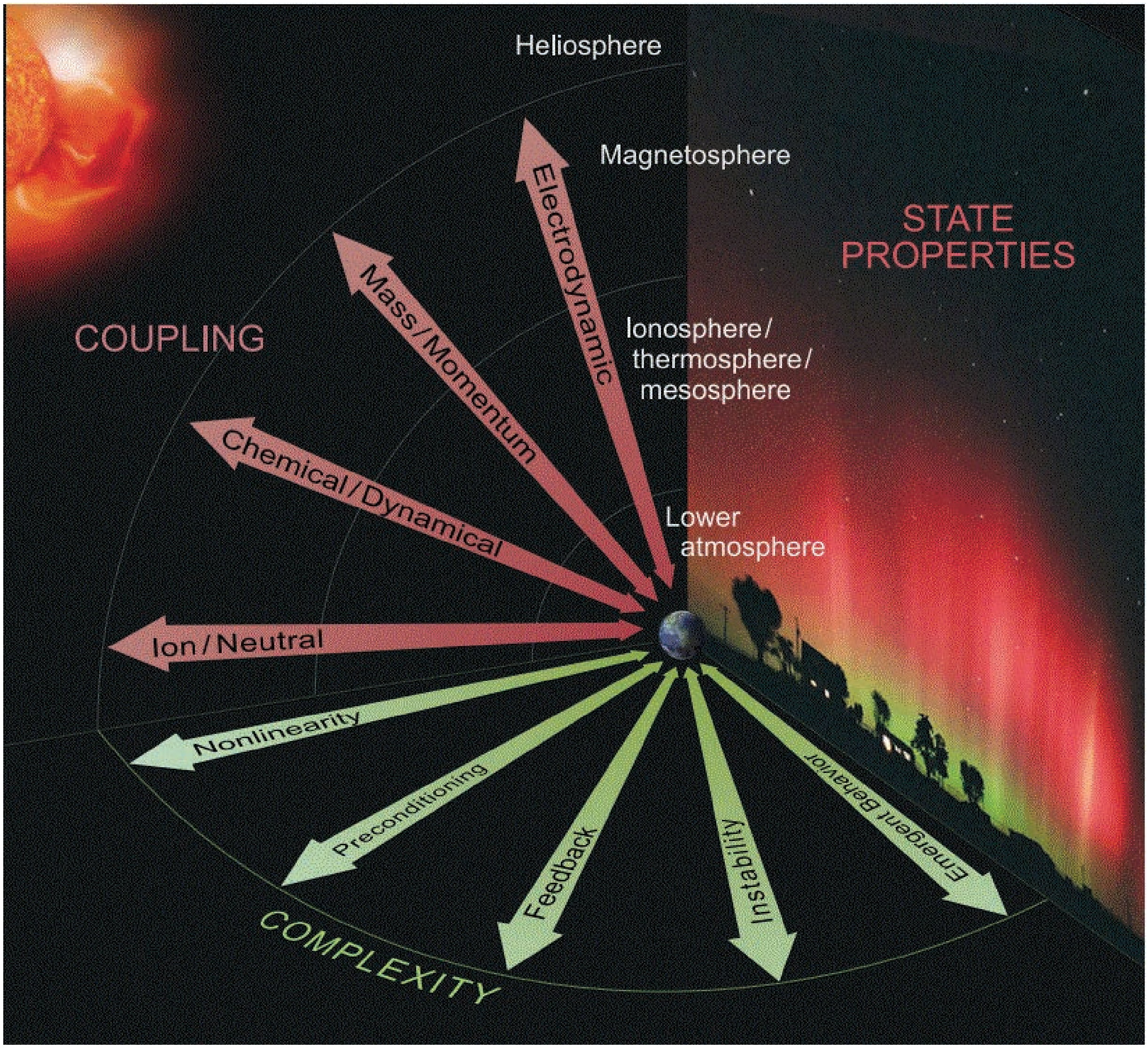


FIGURE D-1 Observable ionosphere–thermosphere–mesosphere (ITM) state properties are coupled through physical processes (red arrows) that have been traditional focus areas of research. However, the ITM is a complex dynamical system that simultaneously manifests nonlinearity, preconditioning, feedback, instability, and emergent behavior (green arrows).
SOURCE: CEDAR (2011), https://cedarscience.org/sites/default/files/2021-10/CEDAR_Plan_June_2011_online.pdf.

National awareness of the importance of the ITM region to U.S. infrastructure has grown in recent years, as demonstrated by the establishment of the 2019 National Space Weather Strategy and Action Plan (SWSAP) (NSTC 2019) and the 2020 Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT 2020). The ITM manifests many different space weather phenomena that are known to adversely affect numerous technological systems and applications in the public and governmental sectors. It is imperative that the ITM community make significant progress in the fundamental understanding of the ITM as an interconnected system if we are to meet society's space weather forecasting needs and fulfill obligations defined by the PROSWIFT Act.

A transformation in the approach to implementation is required to support ITM's system science focused goals. The traditional paradigm of isolated and often temporary observational platforms and experiments within the discrete ionosphere, thermosphere, and mesosphere regions is no longer adequate. Beginning with the key system science–centric GDC and DYNAMIC missions, the next decade's implementation strategy emphasizes multipoint, multistate observations and well-coordinated heterogeneous observations that together address the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the National Oceanic and Atmospheric Administration (NOAA) priorities and needs.

Overall implementation strategy: Conduct research within a system science paradigm that emphasizes the complex linkages between different regions, scales, domains, and processes of the ITM; quantifies the relative roles of competing causal pathways; and establishes the baselines from which emergent behavior can be distinguished.

The implementation strategy presented in this panel report requires investment in new approaches to conducting ITM research, such as harnessing opportunities to access space, establishing distributed and heterogeneous ground-based instrument networks, and utilizing next-generation data science tools and modeling.

Programmatic implementation strategy: Establish an overarching interagency framework to coordinate the use of diverse assets for ITM research throughout all programmatic levels.

A key part of achieving these system science goals in the next decade can only be realized through the observations provided by the GDC and DYNAMIC missions, flying jointly. By simultaneously observing key ion, neutral, chemical, and electrodynamic parameters in multiple local time and longitude sectors, GDC and DYNAMIC will provide the crucial foundation upon which to grow ITM system science, especially when tightly coordinated with ground-based sensors, which provide key altitude-resolved information within rapid and highly variable ion-neutral interaction pathways, and models, which provide insight into the underlying physical processes that govern the observed responses.

Foundational implementation strategy: Within the next decade, implement the primary GDC and DYNAMIC missions contemporaneously and ensure the availability of strategic ground-based observational assets and modeling.

In summary, the ITM is a unique natural laboratory that is invaluable for advancing interdisciplinary science. The priority science goals and objectives defined in Sections D.3 and D.4, along with the implementation strategies defined in Sections D.5 and D.6, reflect the tremendous benefit of transforming the ITM community's focus toward system science investigations that advance both fundamental and applied knowledge. The ITM community is well positioned to make incredible scientific progress over the next decade through the implementation of the strategies described in this report. These efforts are well suited to promote engagement and training of the next generation of scientists and engineers, thus ensuring a vibrant future for ITM system science.

D.2 CURRENT STATE OF IONOSPHERE–THERMOSPHERE–MESOSPHERE SCIENCE

Over the past decade, the ITM community made significant advances in the understanding of the ITM system through projects and vigorous programs promoted at the community, national, and international levels. Diverse programs within agencies, as well as initial multiagency efforts, resulted in scientific discoveries of new phenomena and expanded understanding of the interconnection and importance of the underlying physics to the overall geospace system. These important findings have only reinforced the growing need for a holistic, system-focused approach to ITM research that emphasizes understanding the vast transition in governing physics over this altitude range in near-Earth space, which is critical to modern technological society.

A common hallmark of recent discoveries, emphasizing the need for system approaches, is rooted in the community's growing understanding of the large number of simultaneous pathways and processes spanning the ITM, both within and external to it. Most components of the upper atmosphere interact in two-way feedback loops, including lower atmosphere forcing of the upper atmosphere, dynamic ion-neutral coupling, and variable solar and magnetospheric influences.

Studies of the ITM system forcing during natural events revealed the importance of coupled dynamic processes. The August 2017 total solar eclipse, traveling over the heavily instrumented continental United States, revealed a rich spectrum of propagating ionospheric disturbances during the supersonic eclipse shadow passage.

This unique event drove advances in whole atmosphere modeling capabilities and quantitative understanding of nonuniform solar extreme ultraviolet (EUV) flux influences on ITM ionization. The resulting whole atmosphere model improvements were also part of general Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) community progress in multiscale and data-driven modeling along with data assimilation. Such efforts are broadly important and provide insights into long-standing problems such as a quantitative understanding of sunset and sunrise ionospheric dynamics, ionospheric variability (important for space weather and its operational effects), ion-neutral coupling, and preconditioning influences.

The 2022 Hunga Tonga–Hunga Ha'apai underwater volcanic eruption provided a rare example of extreme natural forcing that spurred community efforts into understanding whole ITM system responses to forcing. The eruption injected huge amounts of water vapor into stratospheric circulation and launched a myriad of atmospheric waves that were unexpectedly observed to propagate around the world several times. The ITM response also included large-scale ionospheric electron density depletions extending well beyond equatorial latitudes. This unprecedented forcing event has accelerated efforts to use the ITM system-wide Tonga response to better understand whole atmosphere coupling through studies that emphasize the importance of gravity wave forcing from the lower atmosphere, filtering effects of wave breaking and regeneration in the mesosphere and lower thermosphere, subsequent driving of pronounced ionospheric features, and the role of background thermospheric winds in mediating transient behavior.

Significant progress in the past decade has been made on the long-standing topic of the ITM's complicated response to magnetic storms. The severe effects of the St. Patrick's Day 2013 and 2015 storms, along with combined coronal mass ejection (CME) and intense X-class solar flare impacts in the strong September 2017 event, have shown that both ionized and neutral ITM components have dynamic responses (e.g., neutral wind surges driven by intense cross-field ion flows) with different relative influences and recovery times. During storms, deep ionospheric electron density depletions, known as "super-bubbles," have been observed during storms to extend across a wide range of background magnetic field angles, from equatorial latitudes to the plasmasphere boundary layer, challenging traditional regional-based concepts of ITM electrodynamic coupling and demanding a holistic approach to their analysis.

In recent years, researchers analyzing historical data from the Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS) and Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite missions discovered that the neutral exosphere also exhibits large density perturbations in response to geomagnetic storms. Because these disturbances span thousands of kilometers across Earth's near-space environment and involve thermal and nonthermal coupling of the exosphere with ambient ions and neutrals, a complete understanding of their origin and impact on the geospace system requires a systems science framework. NASA's Carruthers Geocorona Observatory, a NASA Heliophysics science mission of opportunity scheduled for launch in 2025, will provide the first dedicated observations of global exospheric structure and dynamics needed to assess the role of exospheric charge exchange in mediating both atmospheric escape as well as the geospace response to geomagnetic storms, through the dissipation of magnetospheric ring current energy and the ionospheric replenishment of storm-driven plasmaspheric depletions.

Ion-neutral charge exchange is a fundamental ITM process during quiet geomagnetic conditions as well, particularly between singly ionized oxygen (O^+) and neutral atomic oxygen and hydrogen (O and H), the dominant constituents in Earth's upper atmosphere. Because O-O^+ charge exchange transfers momentum and energy between the ionosphere and thermosphere, the cross section governing this interaction strongly influences calculations of plasma drift speeds, diffusion coefficients, frictional heating, and the altitude distribution and density of the ionospheric F-region. Recently, using a decades-long baseline of optical and radar data acquired from the Arecibo Observatory, historical discrepancies among aeronomical estimates of O-O^+ charge exchange efficacy were reconciled with modern theoretical calculations, and recent laboratory measurements were found to be consistent with the ionospheric data. Resolution of this long-standing controversy has reduced a major source of physics-based model uncertainty and established O^+ momentum and energy balance techniques as a reliable means of ground-based remote sensing of thermospheric O density using altitude-resolved data from IS radar facilities.

Over the past decade, a few space-based missions have also yielded long temporal baselines of ITM parameter measurements through their serendipitous continuation in operation well beyond their planned lifetimes. As the sixth oldest Heliophysics Division mission in operation, the TIMED satellite has provided nearly continuous, high-cadence observations of the solar EUV flux as well as mesospheric temperature and composition over its more than 20-year operational span. These data have revealed significant mesospheric cooling trends with strong spatial dependencies. Mesospheric cooling was also observed by the Aeronomy of Ice in the Mesosphere (AIM) mission, based on its own 16-year duration of observations of noctilucent cloud formation at polar latitudes. Whole atmosphere modeling studies have long indicated that these observed ITM cooling trends are harbingers of global climate change in response to anthropogenic changes in atmospheric composition at Earth's surface. Models also predict that the response of the ITM system to Earth's climate evolution is highly complex, involving not only temperature and density variations but also changes in mesospheric chemistry, gravity wave generation, atmospheric circulation, and more.

Much progress has been made recently in improving the understanding of the ITM as a dynamically coupled system subject to variable external and internal drivers, particularly regarding the coupling between neutral and plasma populations. For example, the Ionospheric Connection Explorer (ICON) mission provided the first wide-scale observational quantification of the significance of atmosphere–ionosphere coupling mechanisms (e.g., dynamo electric fields, ion drag, and composition carried by tides and planetary waves) using coordinated measurements of low-latitude neutral winds, plasma flows, composition, and densities. In particular, ICON revealed the importance of neutral winds at 100–150 km altitudes in driving ionospheric variability. The Global-scale Observations of the Limb and Disk (GOLD) mission, with its unique geostationary fields of view, has enabled observations of the lower thermosphere temperature and composition, as well as the ionosphere, at an unprecedented temporal and spatial resolution. GOLD has used these capabilities for multiple scientific findings, including the unanticipated range of variability and structure of the nighttime ionosphere, especially of the Equatorial Ionization Anomaly. GOLD also revealed complex structures in neutral composition (O/N_2 ratio) based on observations of airglow generated by conjugate photoelectrons. Both GOLD and ICON observations have also shown the high sensitivity of the ITM to magnetospheric forcing even for the case of relatively small disturbances occurring during solar minimum.

Meanwhile, other ITM ion-neutral coupling investigations have revealed new and unexpected pathways. One example is the Weddell Sea Anomaly, which is characterized by the midnight summertime electron density in the Southern Pacific Ocean exceeding the midday electron density by a factor of 2. Because of the correlation with magnetic field declination and inclination in this region, the phenomenon was long attributed to the action of neutral winds. However, recent model analyses, constrained by key satellite data, showed that neutral thermospheric composition is a much more important influence on ionospheric density than the winds, with similar results explaining northern summer anomalies west of the Bering Sea. Such studies highlight the acute community need to better understand neutral composition dynamics as a means to understand charged species behavior.

Midlatitude and subauroral regions also exhibit dynamic features that challenge conventional understanding. Storm-time deep electron density depletions, driven by and associated with complex electrodynamic forcing and intense neutral flows, have unexpectedly been found stretching continuously from equatorial regions through mid-latitudes into the plasmasphere boundary layer. Optical signatures with unusual spectrographic properties, such as subauroral emissions (Strong Thermal Emission Velocity Enhancements [STEVEs]) containing both broad spectral features and spatially structured emissions, have been discovered well equatorward of the aurora with unexpected connections to long-known stable auroral red (SAR) arc signatures in the ring current footprints. STEVE features are associated with extreme and unusual fine-scale plasma and neutral atmospheric dynamics, including highly supersonic ion flow velocities (~5–10 km/s or more) and extreme electron temperatures (>6,000 K), conditions that lie at the edge of current modeling capabilities. Furthermore, the transformation of the subauroral region into these extreme conditions can occur within minutes. These newly discovered phenomena significantly challenge the understanding of ITM electrodynamics and aeronomy, given the limitations of available instrumentation and the sparsity of observations both spatially and temporally.

The auroral region, in contrast, is relatively well instrumented, and significant progress has accordingly been made over the past decade in understanding ITM coupling to the magnetosphere at high latitudes, particularly regarding the magnetospheric source of pulsating aurora and its associated energy input as well as auroral generation mechanisms related to field-line-resonance arcs. Beyond terrestrial systems, this understanding of Earth's auroral system has been applied to new observations at Jupiter by the Juno satellite, where many of the same processes (and a few others) work together in a very different morphology. For instance, on Jupiter, bidirectional broadband auroral particle acceleration dominates, leading to visible features even in downward current regions. This formerly confusing signature is now understandable owing to an improved understanding of similar processes operating at Earth.

The past decade has also seen an increased recognition, through numerous serendipitous observations, of direct magnetosphere–ionosphere coupling effects from high-energy particle precipitation >1 MeV at auroral latitudes that generates odd nitrogen oxide (NO_x) deep within the lower atmosphere. Subsequent transport greatly accelerates persistent, catalytic ozone loss in the polar winter. Understanding these important processes, and their feedback connections, is truly a system-scale challenge and awaits a comprehensive coupled whole atmosphere modeling and dedicated observational effort that includes constraints on energetic particle populations in the overlying magnetosphere.

The preceding summary of the current state of knowledge about the ITM is necessarily incomplete, but the examples mentioned in this section illustrate the significant and exciting progress that has been made over the past decade. However, despite this success, much more remains to be learned about the fundamental processes that govern the complex ITM response to its highly variable and evolving system drivers on multiple scales. The next section describes a set of PSGs and focused science objectives, which are designed to motivate the next decade's development of observational, modeling, and data analysis capabilities needed to advance understanding of the ITM as a dynamic system within the broader geospace system as a whole.

D.3 PRIORITY SCIENCE GOALS FOR IONOSPHERE–THERMOSPHERE–MESOSPHERE PHYSICS

The discoveries described in Section D.1 point to a compelling need for system science approaches to ITM research. This need arises from the scientific requirement to comprehensively understand the vast number of processes acting simultaneously within this region. Developing this understanding requires approaches that accommodate the observational, modeling, and theoretical challenges posed by the wide variety of interactions between neutral and ionized species over the altitude ranges spanned, along with the collective effects of processes that range over many decades in both spatial and temporal scales.

Accordingly, the ITM panel has codified the needed system science framework into four PSGs for the 2024–2033 decade. These goals are enumerated and expanded on throughout the remainder of this section. Addressing these goals in a system science framework provides an exciting and transformational pathway toward an ultimate and vital understanding of the atmospheric regions closest to Earth and its inhabitants, along with the dynamic effects of variations in those regions on society and technology.

D.3.1 Priority Science Goal 1: How Are Mass, Momentum, and Energy Exchanged and Transformed at Boundaries Across and Within the ITM System?

The ITM is never an isolated system because it is strongly influenced by neutral particle composition, flows, and temperature variations originating from the stratosphere below and from the magnetosphere and plasmasphere above. The forcing that emerges from the stratosphere includes momentum and energy transfer from gravity waves and sudden stratospheric warmings. The coupling to higher altitudes includes absorption of solar radiation, plasma transport between the ionosphere and plasmasphere, and gravitational escape of light neutrals. In addition to these external boundaries, internal transitions in governing physics constitute another important type of boundary in the ITM system. The transformation of mass, momentum, and energy across these internal transition regions has a profound influence on both the equilibrium behavior and dynamics of the ITM state. Feedback across both external and internal boundaries is almost always bidirectional and can be highly sensitive to initial conditions (preconditioning).

In the 2013 solar and space physics decadal survey (NRC 2013; hereafter the "2013 decadal survey"), multiple science goals of the Panel on Atmosphere–Ionosphere–Magnetosphere Interactions (AIMI) focused on interactions across external ITM boundaries. AIMI Science Goal 1 ("How does the IT system respond to, and regulate, magnetospheric forcing over global, regional, and local scales?"), AIMI Science Goal 2 ("How does lower atmosphere variability affect geospace?"), and AIMI Science Goal 3 ("How do high-latitude electromagnetic energy and particle flows impact the geospace system?") all recognize the importance of inputs to the ITM system in driving the steady state and dynamical behavior of the system. The panel finds that these science goals of the previous decade are valuable and can be built upon to inspire innovative research in the next decade.

However, although great progress was made with the 2013 AIMI science goals that focused on isolated regions and physical processes, this narrow focus is not sufficient for future ITM progress, which demands a strong systems science approach. In particular, the previous decade's strategy treated input drivers separately without fully allowing for the very important complex, nonlinear interaction of drivers that can occur at the same time. Furthermore, the previous strategy did not sufficiently focus on interactions across important internal boundaries of the ITM system. For these reasons, ITM science needs to directly address these gaps by explicitly incorporating both external and internal exchanges and transformations at boundaries.

The following sections describe specific scientific objectives identified by the panel within PSG 1 for which significant progress can be achieved in the next decade.

Priority Science Goal 1, Objective 1.1: Determine the Mechanisms of Energy and Momentum Transformation and Exchange During and After Extreme Impulsive Events

For decades, study of variability in the ITM system has involved elucidating the response to geomagnetic storm forcing, which manifests as sharp impulsive inputs through such events as interplanetary magnetic field reconfigurations associated with coronal mass ejections. (See Appendix B for more details.) Through multiple mechanisms including electrodynamic, composition, and kinetic pathways, geomagnetic storms trigger large and complex perturbations in all ITM state variables on multiple temporal and spatial scales. Understanding this storm-time forcing and its impacts on system response is by no means a closed topic and remains a vital part of community research. Alongside these efforts, the past 2 decades have seen a great deal of additional attention paid toward another vital element in the ITM dynamic picture, through observing and modeling the importance and impacts of transient event influences from the lower atmosphere. These events force significant ITM dynamic wave responses in the form of phenomena such as traveling ionospheric disturbances (TIDs) and traveling atmospheric disturbances (TADs). For example, the massive submarine volcanic eruption of Hunga Tonga–Hunga Ha'apai drastically increased stratospheric atmospheric water vapor concentrations and generated a large ITM system response, which manifested in part as globally propagating waves (Figure D-2). Additional examples of extreme, impulsive external forcing on the ITM include tsunamis, tornadoes, human events (explosions), coronal mass ejections, and solar flares.

For the study of these extreme events, the current research strategy integrates space-based missions, ground-based instrumentation, theory, and modeling, which are essential to properly elucidate mass, momentum, and energy exchange for these events. For example, NSF CEDAR and NASA's upcoming DYNAMIC mission study how wave action drives ITM energetics and dynamics, and therefore will capture and measure the impacts on the ITM from extreme and transient events.

Priority Science Goal 1, Objective 1.2: Determine the Time-Varying, Two-Way Electrodynamic Linkages and Mass Flow/Transport Processes Between the Ionosphere, Plasmasphere, and Magnetosphere

Magnetospheric and ionospheric processes (and associated ITM dynamics) are tightly coupled on multiple spatial and temporal scales through a variety of mechanisms. For example, the Birkeland Region 1 upward field-aligned currents (downward electron precipitation) within auroral regions cause conductivity variations that feed back on electron acceleration. Field-aligned heat conduction at subauroral latitudes in the Region 2 field-aligned current (ring current) footprints during storm periods leads to significant ionospheric and thermospheric temperature increases associated with SAR arcs. Electrodynamic feedback mechanisms in the subauroral regions lead to multiple responses. For example, broad (degrees wide) ionospheric flow channels known as subauroral polarization streams (SAPS) carry significant heavy ion mass to cusp outflow regions with subsequent travel out to the

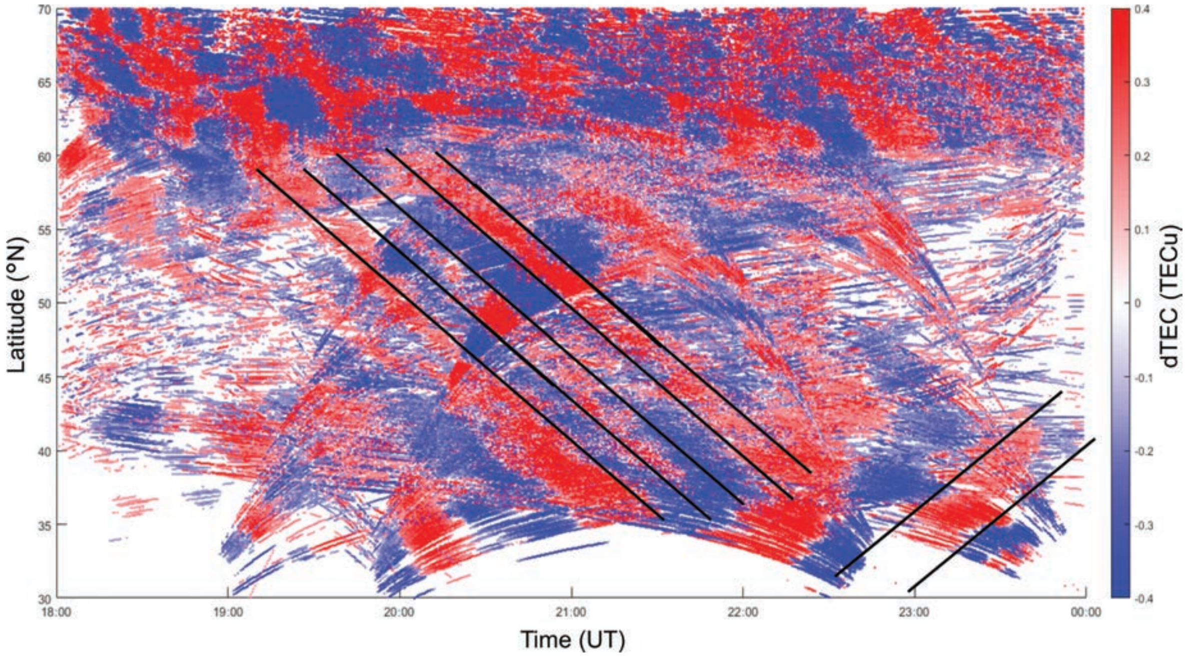


FIGURE D-2 Multi-instrument detection in Europe of ionospheric disturbances caused by the January 15, 2022, eruption of the Hunga Tonga–Hunga Ha‘apai volcano.
SOURCE: Verhulst et al. (2022), https://www.swsc-journal.org/articles/swsc/full_html/2022/01/swsc220017/swsc220017.html. CC BY 4.0.

inner magnetosphere. Electric fields and currents lead to narrow, highly supersonic ionospheric flows known as subauroral ion drifts (SAIDs) and fine-scale neutral atmospheric responses known as STEVEs.

The current ITM science program implementation strategies reflect the importance of these physical processes. The NSF CEDAR and GEM programs work to understand how Earth’s atmosphere is coupled to its magnetosphere through observations, theory, and increasingly realistic models, and the current NASA Heliophysics strategy focuses on the interaction of the extended solar atmosphere with Earth. NASA’s GDC and DYNAMIC’s multiplane, multi-altitude constellation will observe critically needed information on electromagnetic ITM system inputs and responses at mid- and high latitudes. Mid- and high-latitude incoherent scatter (IS) radars (Millstone Hill, Poker Flat IS Radar [PFISR]/Resolute Bay IS Radar [RISR]) provide local and regional fine-scale altitude-resolved measurements of key ionospheric state variables (electron and ion density, plasma temperature, and plasma drifts) at both subauroral/midlatitudes and high latitudes. Ground-based all-sky imagers and Fabry-Pérot interferometers have long used airglow to study the occurrence and causes of auroral arcs and have recently also studied neutral response to extreme subauroral phenomena such as STEVE.

PSG 1 embraces these space- and ground-based sensing tools and motivates their continued use by affirming and emphasizing the ongoing need to understand the two-way coupling between the ITM, plasmasphere, and magnetosphere. More accurate representation and understanding of this coupling will advance knowledge of the transfer and transformation of mass, momentum, and energy, which pervades the ITM system response to these inputs.

Priority Science Goal 1, Objective 1.3: Determine How the ITM Responds to Lower Atmosphere Forcing on Local and Global Scales

The ITM system has been shown to be extremely sensitive to lower atmosphere forcing, especially during periods of minimal solar activity. The 2013 decadal survey recognized the importance of lower atmosphere forcing on the ITM. However, there remain multiple critical and unresolved issues relating to the impact of the lower atmosphere on the ITM and how the ITM responds on local and global scales. For example, the state of the stratospheric vortex has been recently shown to significantly alter the composition of the lower thermosphere. Figure D-3 shows the NASA GOLD mission's observations of O/N_2 composition during a sudden stratospheric warming (SSW) event, where O/N_2 is depleted during this event. Open questions remain about how the circulation is altered owing to the state of the vortex and how the composition is altered in both latitude and longitude.

A heterogeneous approach to observation and analysis is required to further elucidate the forcing of the lower atmosphere on the ITM system. The current NSF CEDAR strategy, "CEDAR: The New Dimension" (CEDAR 2011), reflects this approach by employing theory, modeling, and observations from both ground-based and space-based platforms to study changes in the whole atmosphere with a strong emphasis on system science. The TIMED mission is an example of a current extended mission that provides a more than 20-year observational baseline for studying the energy transfer into and out of the mesosphere and lower thermosphere. In the next decade, it will be important to make continuity of measurements a priority for the successful closure of this science objective. The upcoming DYNAMIC mission will provide critical information about the forcing from below that comes from waves and tides and, depending on mission configuration, can also separate in situ forcing from upward-propagating tides. Furthermore, the simultaneous availability of DYNAMIC and GDC observations is an essential need for this area through characterizing tides in the 110–250 km "thermospheric gap" (DYNAMIC) at the same time as understanding day-to-day tidal variability and mean state variability with good spatial and temporal coverage (GDC).

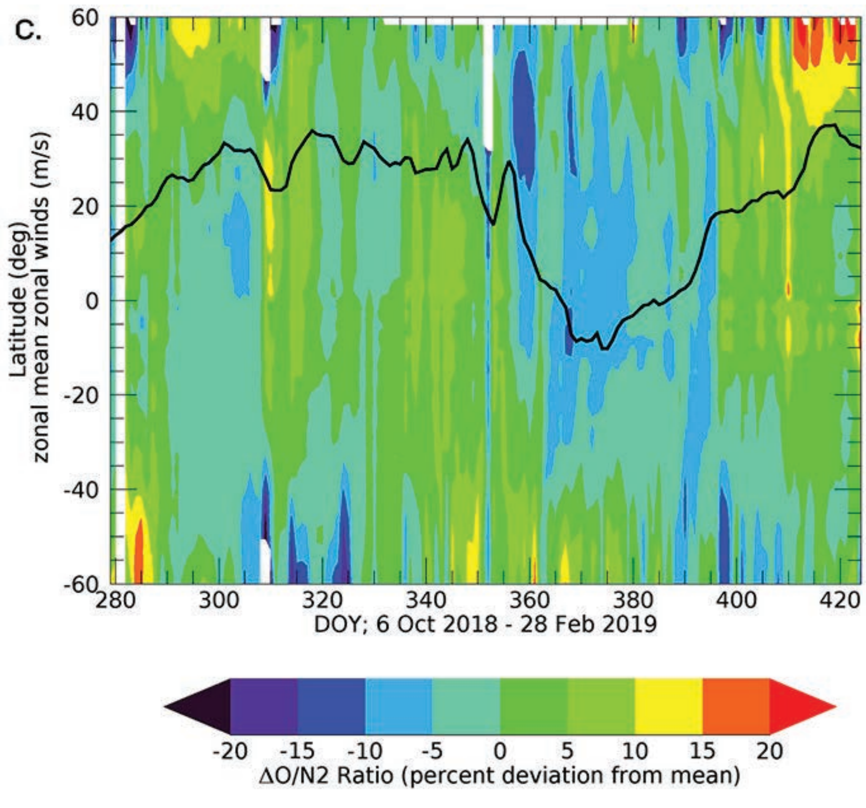


FIGURE D-3 Time series of O/N_2 daytime means averaged (mean, annual, and semiannual components removed), over all observed longitudes as a function of geographic latitude (color contours), along with 10 hPa mean zonal winds in the stratosphere at 60°N from Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) (black line). An SSW occurred around day 370 with onset on day 355.
SOURCE: Oberheide et al. (2020).

Priority Science Goal 1, Objective 1.4: Elucidate the Mechanisms That Govern the Transition in Chemical, Dynamical, and Thermal Drivers Across the ITM from ~100–200 Kilometers

Within the lower thermosphere and ionosphere, many state parameters within the region between 100–200 km exhibit complex transitions as a function of altitude. For example, one set of tides and waves dominates at the lower end of this altitude range, but a pronounced transition to a different set of tides and waves occurs at higher altitudes, as shown in Figure D-4. The altitude, location, and timing of this transition is still unknown, as well as the processes that govern it. It also remains unclear what the variation in behavior is for this important transition on hourly, daily, and seasonal timescales. Closing these knowledge gaps is critical to forward progress.

Efforts to date have focused on addressing these knowledge gaps in several areas. ITM PSG 1 encompasses NASA's Heliophysics Division strategy through the science of examining drivers and inputs into the ITM system.

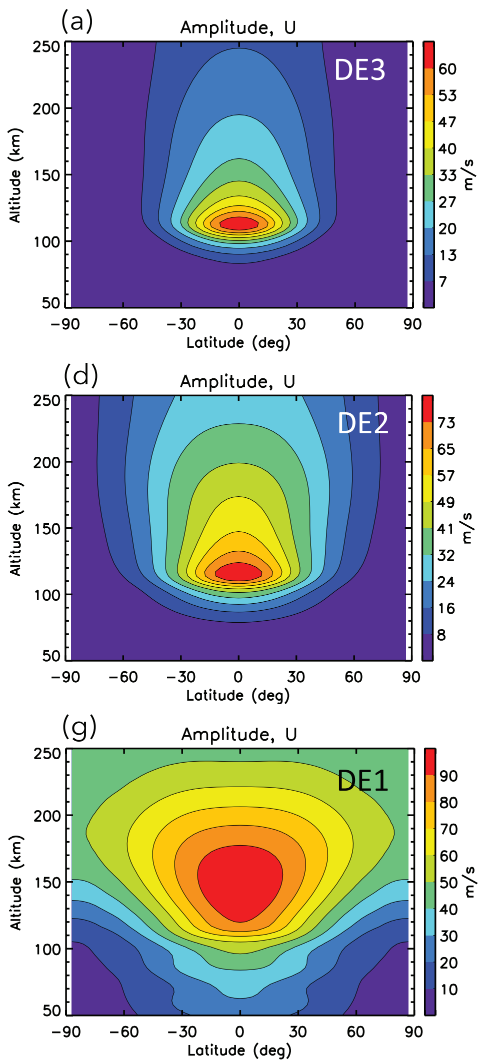


FIGURE D-4 Height versus latitude distributions of amplitude of zonal wind for Hough Mode Extensions (model) of different tides (DE3 mode [*Top*], DE2 mode [*Middle*], and DE1 mode [*Bottom*]) corresponding to F10.7 = 125 s.f.u. These calculations indicate that different tides should dominate at different altitudes. However, very few relevant observations are currently available. SOURCE: Forbes and Zhang (2022).

NASA's planned DYNAMIC mission will focus on how wave action alters this transition region through remote sensing techniques. These mission goals directly address PSG 1.4 by affirming the need to understand the chemical, dynamical, and thermal drivers of the 100–200 km transition region. This transition region is also of special interest to the current NSF CEDAR program that employs theory, modeling, and observations from ground-based and space-based platforms to study changes in the ITM. Within the observational portfolio, light detection and ranging (LiDAR) instruments enable investigations of vertical life cycles of small-scale waves as they propagate into, and break within, the mesosphere and thermosphere. PSG 1.4 encourages the further extension of LiDAR technologies to higher altitudes. This capability increases understanding of these small-scale waves and how they transfer energy and momentum throughout the system. To match current and future expanded capability, cutting-edge modeling has focused on how this transition region is modified by and controlled by waves.

Synopsis of Priority Science Goal 1

Advancing ITM system science in the next decade requires a thorough understanding of those influencing factors that flow across both external and internal boundaries. To optimally study ITM system behavior in the areas of transformations and exchanges across these important delineating regions, the panel's identified science objectives are summarized here:

1. Determine the mechanisms of energy and momentum transformation/exchange during and after extreme events (e.g., volcanic eruptions, geomagnetic storms).
2. Determine the time-varying, two-way electrodynamic linkages and mass flow/transport processes between the ionosphere, plasmasphere, and magnetosphere.
3. Determine how the ITM responds to lower atmospheric forcing on local and global scales.
4. Elucidate the mechanisms that govern the transition in chemical, dynamical, and thermal drivers across the ITM from ~100–200 km.

D.3.2 Priority Science Goal 2: How Do Internal ITM Processes Transform Energy and Momentum Across a Continuum of Spatial and Temporal Scales?

The key state parameters of the ITM system exhibit structure over spatial and temporal scales spanning several orders of magnitude (see Table D-1). The largest scales cover a significant fraction of Earth's circumference. Planetary waves and the diffuse aurora are examples of large-scale phenomena. The smallest scales, exemplified by phenomena such as acoustic waves and plasma turbulence, are cases for which kinetic theory is needed. Between these scales lie mesoscale phenomena such as gravity waves and discrete auroral arcs.

Certain spatial and temporal scales are more efficient pathways for energy and momentum transfer than others. For example, planetary waves generated in the lower atmosphere often dissipate before reaching ionospheric

TABLE D-1 Definitions of Scale Sizes in the Ionosphere–Thermosphere–Mesosphere System with Example Phenomena and Approaches

Scale Sizes	Small Scale	Mesoscale	Large Scale
Temporal	<1 minute	minutes–hours	>hours
Spatial	<1 km	1–100s km	1,000s km
Example phenomena and approaches	• Acoustic waves • Plasma waves and irregularities • Auroral filamentation • Wave–particle interactions • Particle-in-cell codes • In situ sampling	• Gravity waves • Auroral convection • Discrete auroral arcs • Magnetohydrodynamics • Constellations or networked sampling	• Tides/planetary waves • Mean circulation • Polar vortex • Diffuse aurora • Whole atmosphere models • Ionospheric electrostatics • Synoptic sampling

altitudes. However, nonlinear interactions can imprint planetary-wave signatures upon tides, which propagate to the ionosphere and modulate it with planetary-wave periodicities. Another example is eddy diffusion, which is effective at driving large-scale transport of heat and constituents such as O and NO from the lower and middle thermosphere to the mesopause region. Recombination of O is a major energy source for the mesosphere. Such pathways directly impact the global mean temperature profile and in turn atmospheric stability and the upward propagation of waves. For these reasons, understanding vertical atmospheric coupling is not possible without understanding how wave energy and momentum are transformed across scales. These are just two of many examples, discussed below, that support the notion that bidirectional feedback across scales—a process known as "cross-scale coupling"—is a critical element of ITM system science.

For many important processes, cross-scale coupling is mediated by mesoscale processes. For example, gravity wave propagation is regulated by large-scale background flows associated with tides and planetary waves, while gravity wave dissipation drives global circulation and seasonal temperature changes in the mesosphere and lower thermosphere (MLT). Another example is the coupling of the magnetosphere and ionosphere: small-scale precipitation structures generate ionization, which is advected by high-latitude convection, yielding meso-scale conductivity enhancements that feed back to modulate global distributions of electric potential, field-aligned current, and precipitation. The role of mesoscale processes in transforming energy and momentum in the ITM is a significant knowledge gap to be addressed in the next decade.

A challenge for understanding cross-scale coupling is that no single investigative technique is suitable for all scales. For example, incisive vertically resolved observations, which are required to understand energy and momentum transfer, are often available only from isolated ground-based facilities or single-spacecraft missions and cannot observe the global drivers or responses. The modeling challenge is that it has been numerically impractical to capture realistic small-scale gravity wave effects or plasma irregularities in global first-principles models. Also, these models are inherently limited by the availability of high-resolution data for assimilation and validation. Overall, progress on cross-scale coupling has been hampered by siloed investigations and insufficient coordination of expertise.

The importance of cross-scale coupling for ITM science has been recognized for many years. The 2013 decadal survey AIMI report recognized that "cross-scale coupling processes are intrinsic to atmosphere-ionosphere-magnetosphere behavior." AIMI Science Goal 4 ("How do neutrals and plasmas interact to produce multiscale structures in the AIM system?") addresses one of many fundamental processes, ion-neutral coupling, which plays a significant role in ITM structure and evolution on local, regional, and global scales. However, the AIMI strategy did not explicitly promote investigations into coupling *across* spatial scales, nor did it recognize the importance of temporal cross-scale coupling. Cross-scale coupling is an explicit element of the systems science perspective expressed in "CEDAR: The New Dimension." Grassroots, community-led efforts have been dedicated to cross-scale coupling via multiyear conference sessions, including an NSF CEDAR Grand Challenge. Part of the motivation for the NSF Distributed Array of Scientific Instruments (DASI) program is the need to observe multiple scales simultaneously. The Diversify, Realize, Integrate, Venture, Educate (DRIVE) Science Centers are beginning to enable the larger team structures needed to analyze and model cross-scale coupling problems in the ITM.

The following sections describe specific scientific objectives identified by the panel within PSG 2 for which significant progress can be achieved in the next decade.

Priority Science Goal 2, Objective 2.1: Determine How the Gravity Wave Spectrum Cascades Throughout the Thermosphere and Impacts the ITM System

Gravity waves from the lower atmosphere significantly modulate the mean state and variability of the ITM. The classic example is the apparent paradox of the summer mesopause being the coldest place in the Earth system. Although solar radiative heating is stronger in the summer, the summer hemisphere is adiabatically cooled owing to the strong summer-to-winter circulation driven by gravity wave dissipation, serving as an example of meso-to-large-scale energy transfer. Gravity wave energy can also cascade to smaller scales, driving turbulence. Turbulent mixing in the lower thermosphere controls the vertical profiles of chemical constituents like atomic oxygen and determines the thermal structure of the ITM. Gravity waves that reach the ionosphere can generate TIDs and potentially seed plasma instabilities such as equatorial spread F.

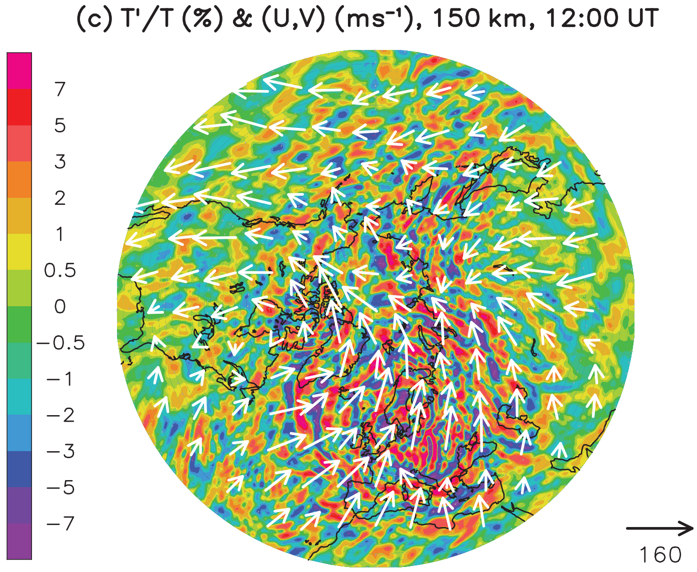


FIGURE D-5 Mechanistic models predict significant higher-order gravity waves in the thermosphere.
SOURCE: Becker et al. (2022).

Gravity wave amplitudes grow with height, a consequence of the conservation of momentum as the neutral density decreases. They can become unstable and break via gravity wave, mean-flow, and nonlinear interactions. This wave breaking is thought to lead to the secondary generation of waves that propagate to higher altitudes. In the thermosphere, this process might repeat in a process known as "multistep vertical coupling." Figure D-5 shows predictions from a mechanistic model of secondary and higher-order gravity waves permeating the winter thermosphere. The relative importance of primary and higher-order gravity waves is still not well understood, and observations of these processes at work remain exceedingly sparse. Whole atmosphere numerical models of these processes are also not yet comprehensive, as they currently either do not include gravity waves or include only a crude parameterization of their effects because there are not enough observations. For instance, some large models are beginning to explicitly simulate gravity waves, but to date only at large scales ($\gtrsim$200 km).

Observational challenges also remain in this area, depending on the technique used. Gravity wave observations have been mostly limited to nighttime and to the lowest altitudes in the ITM (~85–100 km), via ground-based airglow imagery. These observations can target specific airglow emission lines that originate from different altitudes to provide maps of gravity wave propagation. However, the current observation network provides sparse global coverage and is subject to ambiguities associated with their line-of-sight integrated nature. There are promising avenues emerging to address the situation, in the form of networked multistatic meteor radar sites, which are beginning to yield gravity wave characterizations in a limited altitude range (80–100 km). Gravity waves and wave–wind interactions have been observed by LiDARs, albeit with a limited vertical range and at single-point ground facilities. Gravity wave effects on plasma dynamics (e.g., TIDs) are relatively well observed by radars, ionosondes, and networked global navigation satellite system (GNSS) measurements of total electron content (TEC). These instruments observe the dynamic effects of waves modulating the plasma. Nevertheless, the network sensor distribution remains insufficient to comprehensively understand the full range of longitudinal and local time dependence. Observations in the critical 100–200 km region remain extremely rare.

Modeling gravity wave generation and impacts also remains an active and ongoing challenge, because there is not yet a universally understood and elucidated set of mechanisms for wave vertical propagation and their manifestation. For example, the vertical propagation of the spectrum of waves generated by the recent Hunga Tonga–Hunga Ha'apai volcanic eruption in January 2022 is currently serving as a test case for understanding vertical wave coupling. While observed perturbations in the lower atmosphere have been understood as manifestations of the Lamb wave mode, debate is ongoing over the pathways that caused disturbances observed in the ionosphere.

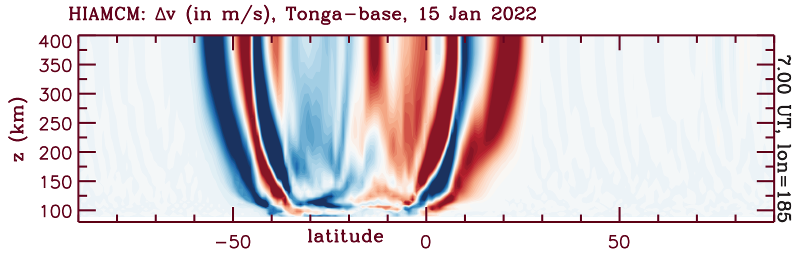


FIGURE D-6 Perturbation meridional wind modeled by the HIAMCM (a mechanistic model), used to interpret the thermospheric Hunga Tonga–Hunga Haʻapai signature as a secondary gravity wave.
SOURCE: Vadas et al. (2023).

Vadas et al. (2023) have argued that the large thermospheric waves are secondary gravity waves generated by the dissipation of the primary waves from the eruption (Figure D-6). Alternatively, Liu et al. (2023) suggest that the L1' Lamb pseudomode may be important for understanding the thermospheric signature (Figure D-7). Resolving the relative importance of these mechanisms will rely in the future on more comprehensive observational databases at altitudes between the mesopause and the ionosphere.

No previous NASA missions have directly targeted gravity wave science. Serendipitous observations of thermospheric gravity waves in the daytime were made by ICON Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI), but only for long wavelengths ($\gtrsim$1,000 km). GOLD conducts rare special campaign modes to observe gravity waves in the disk ultraviolet radiance. Recently launched mission Atmospheric Waves Experiment (AWE) and upcoming GDC will address gravity waves and their effects, but only

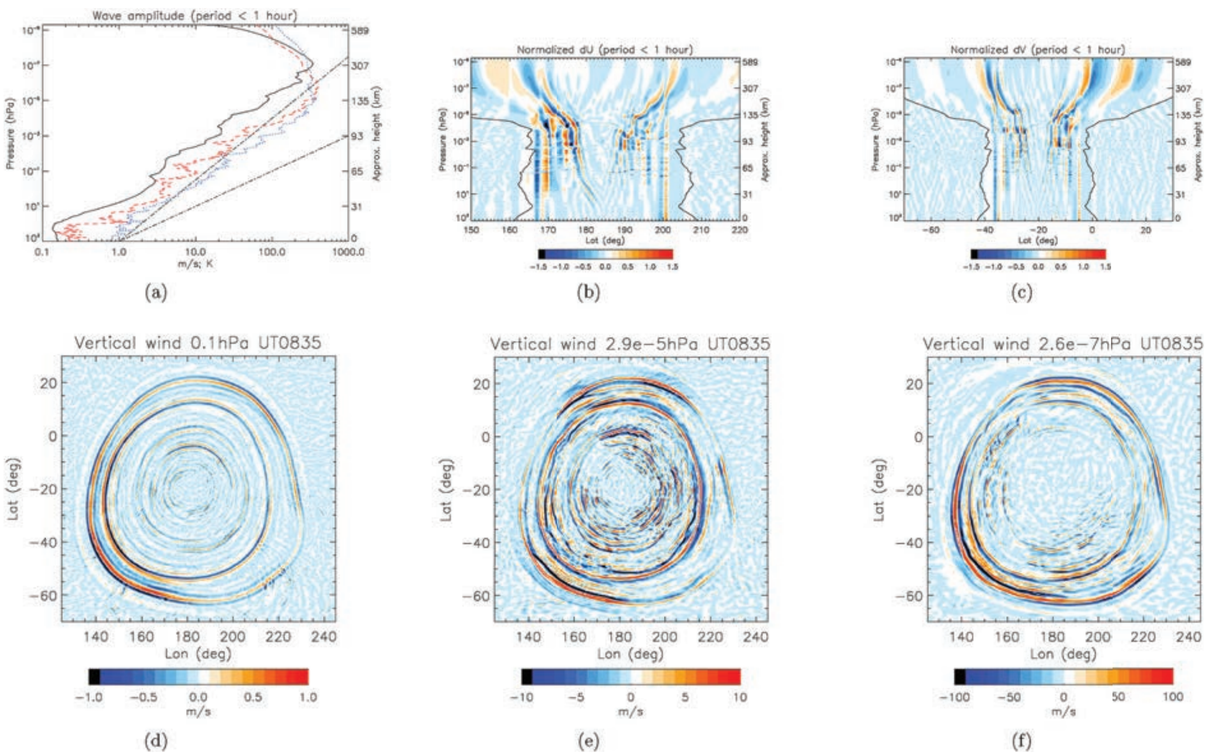


FIGURE D-7 Perturbation vertical, zonal, and meridional winds modeled by the Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X) model. The Hunga-Tonga volcanic explosion offers a discrete test for vertical gravity wave propagation models. Observations show multiscale ionospheric impacts.
SOURCE: Liu et al. (2023), https://doi.org/10.1029/2023GL103682. CC BY.

with snapshots at the upper and lower boundaries. The AWE mission will investigate how gravity wave breaking is influenced by background fields and how momentum deposition then influences the wave field. However, AWE will observe 30–300 km scales only at a single altitude (the OH emission altitude ~87 km) and thus will not address cross-scale coupling or global ITM impacts. GDC will make observations of TIDs and TADs in situ (~400 km) but will not address cross-scale coupling. For these reasons, the panel finds that the vertical life cycle of gravity wave momentum and energy is a key knowledge gap to be addressed in the next decade.

Priority Science Goal 2, Objective 2.2: Determine How Small-Scale Structuring in High-Latitude ITM State Parameters Leads to Mesoscale Conductivity Enhancements That Have Aggregate Global Significance

Small-scale filamentary current structures at high latitudes produce significant local heating and ionization. These structures are embedded within regional-scale and global-scale flow fields that convect the newly ionized or heated gas into undisturbed regions. In turn, these sources modify the global ionospheric conductivity at mesoscales. These modifications of ionospheric conductivity can have global effects, and Figure D-8 depicts how

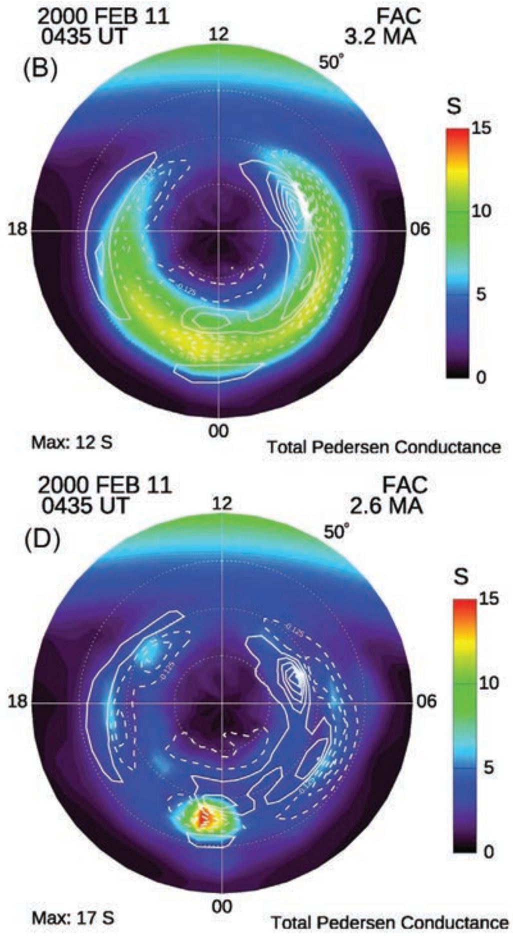


FIGURE D-8 Field-aligned current contours (dashed = upward, solid = downward) and conductance (color) for two cases: Model conductance (top panel) and data-driven, fitted conductance (bottom panel), derived from Polar Ultraviolet Imager auroral images and ground magnetic perturbations, including mesoscale structure.
SOURCE: Reprinted from C. Gabrielse, S.R. Kaeppler, G. Lu, C.-P. Wang, and Y. Yu, 2021, "Energetic Particle Dynamics, Precipitation, and Conductivity," pp. 217–300 in *Cross-Scale Coupling and Energy Transfer in the Magnetosphere-Ionosphere-Thermosphere System*, Y. Nishimura, O. Verkhoglyadova, Y. Deng, and S.-R. Zhang, eds., Copyright (2021), with permission from Elsevier.

modeled potential and field-aligned current patterns can vary dramatically depending on the nature of the input conductance patterns.

The data-driven result in Figure D-9 relied on Polar UVI's full-oval imaging, a capability that has not been available since 2005. Partially filling this measurement gap are ground-based all-sky camera arrays (e.g., Themis ground-based observatory [GBO]), which are suited for investigating arc-scale to regional-scale relationships, but observations are available only at night and only when conditions permit (e.g., during clear skies, new moon phase, and low aerosol levels). Past CEDAR efforts, as well as the European LOcal Mapping of Polar ionospheric Electrodynamics (LOMPE), have combined imagery with magnetometer chains and Super Dual Auroral Radar Network (SuperDARN)/IS radar data to investigate high-latitude cross-scale coupling. However, these successes were not part of a current U.S. research strategy, but instead via international, ad hoc, and often unfunded grassroots efforts.

Electronically scannable IS radars (Advanced Modular IS Radar [AMISR], European IS Scientific Association [EISCAT] 3D) provide vital common-volume measurements across multiple spatial scales nearly simultaneously. Other radar techniques (ionosonde, SuperDARN/high-frequency [HF] radar) also provide compelling measurements with different individual strengths, but they require joint rather than individual analysis to address cross-scale coupling. Meanwhile, whole geospace models (e.g., the Multiscale Atmosphere–Geospace Environment [MAGE] model developed as part of a NASA DRIVE center) have the potential for transformative insights into high-latitude, cross-scale coupling. Such models can self-consistently account for cross-scale, magnetosphere–ionosphere–thermosphere coupling processes.

GDC will provide critical surveys of the spatial scales and persistence times of various phenomena associated with the ITM's response to solar and magnetospheric energy inputs. The phased deployment of the constellation will allow a valuable investigation of individual scales sequentially. However, beyond GDC, coincident observations at various scales remain necessary to assess cross-scale coupling. The upcoming "small mission" Electrojet Zeeman Imaging Explorer (EZIE) (Class D) will investigate current closure at small scales, instantaneously.

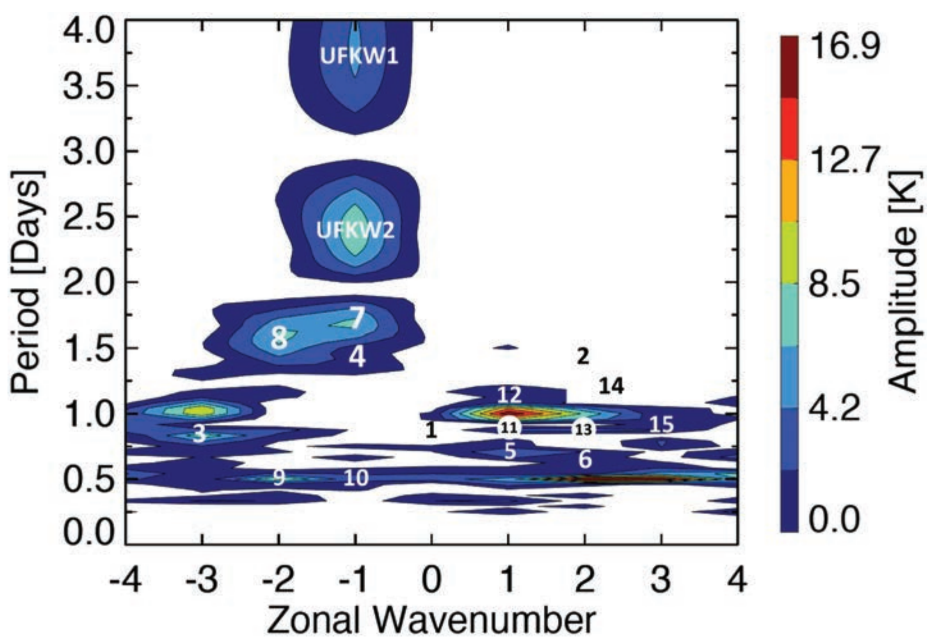


FIGURE D-9 Spectrum of global-scale waves (period versus zonal wavenumber) of thermosphere–ionosphere–mesosphere electrodynamics general circulation model (TIME-GCM)/MERRA2009 temperatures at 120 km during 10 days in April 2009. DE2 and TW3 tides are omitted owing to their large amplitudes. The numbers represent prominent features identified as secondary waves of known primary waves.
NOTE: UFKW, ultra-fast Kelvin wave.
SOURCE: Nystrom et al. (2018).

However, EZIE will address cross-scale coupling phenomena only on a restricted regional scale, not globally. In summary, the panel finds that high-latitude, cross-scale coupling mediated by mesoscale conductivity variability is a key knowledge gap for the coming decade.

Priority Science Goal 2, Objective 2.3: Determine How Nonlinear Coupling Between Mean Neutral Atmosphere Circulation, Tides, and Planetary Waves Drives ITM Variability

A significant amount of observational and theoretical work over the past decade has improved the understanding of how global-scale waves (i.e., tides, planetary waves, and tropical waves) from the lower atmosphere force the ionosphere–thermosphere system. There is direct forcing by penetration into the thermosphere that modifies the chemistry and field-aligned drag, and indirect forcing by altering the neutral wind dynamo. The amplitude of these waves is often nonnegligible relative to the background, in which case second-order terms are important and propagation is nonlinear. This allows for the transfer of wave momentum and energy between different spatial and temporal scales, which can drive a rich spectrum of ITM variability.

The modeling results in Figure D-9 suggest that child waves from nonlinear interactions between primary waves may produce half of the variability of the primary waves at 120 km. Observational evidence for these waves is extremely scarce, often consisting of observations below 100 km, or observations of the plasma response at ~300–400 km, but with little information on the pathways by which these signatures reach the ionosphere. A major observational challenge is that child waves can alias with primary waves in single-spacecraft observations from low Earth orbit (e.g., ICON and TIMED). Full-disk observations from high altitudes (e.g., GOLD) ameliorate aliasing issues, but such remote sensing observations are inherently integrated along the viewing line of sight and are not directly altitude-resolved.

While GDC and DYNAMIC will be foundational for moving this science forward, the missions may still be limited in their ability to completely address nonlinear wave–wave coupling. The DYNAMIC mission is likely to address some aspects of vertically resolved cross-scale coupling within the mesosphere/lower thermosphere, depending on the selected configuration. If DYNAMIC is operated simultaneously with GDC, it will be possible to trace the effects of some wave–wave coupling processes on the middle/upper thermosphere/ionosphere. These contributions will be valuable but inherently limited—for example, if the DYNAMIC budget limits the implementation to two flight elements, it will be difficult to resolve semidiurnal or higher-order tides on subseasonal timescales. Ground-based meteor radar systems distributed around the globe have the potential to provide critical observations of the global neutral wind distribution, but only from ~80 to 100 km.

In aggregate, global-scale wave–wave/mean-flow coupling is a key knowledge gap for understanding ITM variability in the next decade. PSG 2.3 is not necessarily independent of PSG 2.1, because wave–wave coupling processes can include gravity waves. Indeed, the steep wind shears that can cause sporadic E layers are thought to arise from gravity wave/tide interactions. Another example is stratospheric sudden warmings, in which large-scale variations in the polar vortex interact with tides and gravity waves to produce global-scale ionospheric disturbances.

Priority Science Goal 2, Objective 2.4: Determine How Plasma Irregularities Are Driven by and Regulate Large-Scale ITM Phenomena

Plasma turbulence is a frontier of theoretical physics but also has numerous direct applications to heliophysics. Small-scale Kelvin-Helmholtz instabilities are generated by, and subsequently regulate, large-scale and mesoscale flow shears that likely control system-level and emergent behavior of fine-scale flow channels such as SAIDs, and their visible signatures known as STEVEs. The auroral convection pattern has mesoscale variability cascading into small-scale instabilities embedded within its synoptic pattern. Farley-Buneman (cross-streaming) instabilities interact with and limit large-scale flow differences between species. Interchange instabilities (e.g., Rayleigh-Taylor) are associated with large-scale equatorial plasma bubbles, an important space weather phenomenon. The potential seeding of bubbles by gravity waves is still being debated. Plasma instabilities causing 150 km echoes are a nearly 30-year mystery recently hypothesized to be driven by coupling between the upper hybrid instability and background photoelectrons, possibly modulated by gravity waves (Figure D-10).

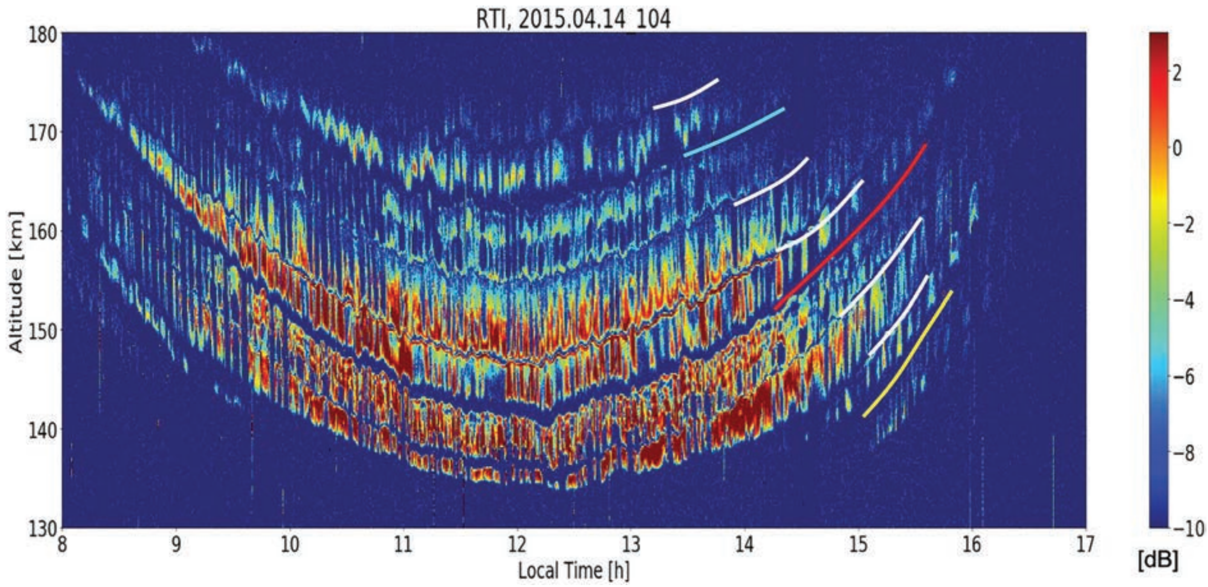


FIGURE D-10 Reflected power (signal-to-noise ratio in dB) from the Jicamarca Radio Observatory vertical beam on April 14, 2015, as a function of time and altitude. This is a signature of so-called 150 km echoes, which have been observed and puzzled over for decades, but significant theoretical advances have been made in the past decade.
SOURCE: Lehmacher et al. (2019).

With some exceptions, irregularity science has focused mostly on processes occurring at the equator (e.g., using the Jicamarca Radio Observatory IS radar) and in auroral/polar regions (e.g., polar cap patches), but large-scale features that can drive instabilities through cross-scale coupling occur across all latitudes. Electronically scannable IS radars have contributed (AMISR) or will contribute (EISCAT 3D) critical observations of multiple scales simultaneously in regional fields of view. Other radar techniques (ionosonde, SuperDARN/HF radar) also provide compelling measurements with different individual strengths. But to comprehensively address cross-scale coupling between irregularities and large-scale ITM phenomena, measurements and expertise at different scales need to be brought together.

In addition to theoretical treatments and bespoke numerical models, general-purpose high-resolution regional modeling of plasma irregularities and plasma-neutral interactions have captured some cross-scale coupling phenomena. Advances in techniques such as adaptive mesh refinement could enable further progress. The panel finds that understanding of the generation of plasma irregularities and their interaction with larger-scale ITM phenomena is a key knowledge gap for the coming decade.

Synopsis of Priority Science Goal 2

In concert with transport across physical boundaries and transition regions (see PSG 1), the internal exchange of energy and momentum across all spatial and temporal scales, including the vitally important mesoscale range, is a fundamental process whose understanding is essential for ITM system science in the next decade. Accordingly, optimal study of ITM system behavior in energy and momentum dynamics requires effort on the panel's identified science objectives, summarized here:

1. Determine how the gravity wave spectrum cascades throughout the thermosphere and impacts the ITM system.
2. Determine how small-scale structuring in high-latitude ITM state parameters leads to mesoscale conductivity enhancements, which have aggregate global significance.

3. Determine how nonlinear coupling between mean neutral atmosphere circulation, tides, and planetary waves drives ITM variability.
4. Determine how plasma irregularities are driven by and regulate large-scale ITM phenomena.

D.3.3 Priority Science Goal 3: Quantitatively, What Is the Relative Significance of Competing Physical Processes That Govern the ITM State and Its Variability?

The ITM is an interconnected system whose response to its multiple drivers can be characterized by nonlinearity and instability, feedback, preconditioning, and emergent behavior. The evolution of the dynamic ITM state (plasma and neutral density, composition, temperature, and velocity) is governed by the continuity, momentum, and energy equations and their derivative terms, which are nonlinear and can be coupled across multiple scales. While the theory that supports data analysis and numerical modeling is well established, quantitative knowledge regarding the numerous driver/response relationships and their relative significance under different conditions (spatial, climatological, temporal) is underconstrained.

The complexity and interconnectivity of the ITM system can lead to interpretations that rely on observed correlations rather than on underlying physical causal links. One such example is the early interpretation of the cause of the Weddell Sea Anomaly, in which the midnight electron density can exceed the midday electron density by a factor of 2 in the Southern Pacific Ocean in the summer. Because of the correlation with the particular magnetic field declination and inclination in this region, the phenomenon was long attributed to the action of neutral winds. Recent analyses with a model that was constrained by key satellite data showed that the neutral composition is a much more important driver of anomalous electron density than wind effects. This example demonstrates the importance of having sufficient data to constrain important model parameters to determine which ones are most effective. Quantifying the relative significance of competing physical processes, as in this example, is a critical step in system science development, leading to full physical understanding as well as predictive capabilities.

A system-level understanding of the ITM requires moving from correlation-based conclusions to the identification of fundamental causative mechanisms. Such a definitive determination is predicated on accurate and precise quantification of the relative significance of competing physical processes. A system-level understanding of the ITM also must establish baseline behavior to enable both the recognition of emergent behavior as well as the assessment of the sensitivity of a response to the specific nature of background conditions.

Both the 2013 decadal survey and the 2011 NSF CEDAR Strategic Plan (CEDAR 2011) introduced system science, particularly system identification, as a valuable framework for ITM science. The 2013 decadal survey recognized the strong role that modeling and theoretical analysis play in advancing a system science approach, specifically noting that comprehensive models of the AIM system would benefit from "developing assimilative capabilities" and "the development of embedded grid and/or nested model capabilities, which could be used to understand the interactions between local- and regional-scale phenomena within the context of global AIM system evolution." It also noted that "Complementary theoretical work would enhance understanding of the physics of various-scale structures and the self-consistent interactions between them." The 2013 decadal survey recommended the implementation of a multiagency initiative, DRIVE, to more fully develop and effectively employ the many experimental and theoretical assets at NASA, NSF, and other agencies to address the need for multidisciplinary data and model integrated investigations of fundamental physical processes.

The proposed PSG 3 supporting strategies in this new decadal survey build on these initiatives and focus future scientific efforts on establishing quantitative, causal links between ITM processes, rather than correlative relationships of unknown significance. The following sections describe specific scientific objectives identified by the panel within PSG 3 for which significant progress can be achieved in the next decade.

Priority Science Goal 3, Objective 3.1: Quantify the Relative Roles of Preconditioning and Seeding Mechanisms in Controlling the Emergence and Evolution of Ionospheric Irregularities

Ionospheric density irregularities are the major source of naturally occurring disruptions of radio frequency transmissions. They span several orders of magnitude in spatial scales (centimeters to hundreds of km) and exhibit strong day-to-day, seasonal, and longitudinal dependencies. While most common at low latitudes and high latitudes, recent research has shown that there are midlatitude fluctuations measurable through rate-of-TEC variations. At high latitudes, convection and auroral precipitation are associated with scintillations. A number of different plasma instability mechanisms—gradient drift, Kelvin-Helmholtz, temperature gradient instability—are thought to contribute but perhaps to differing degrees in different circumstances.

At low latitudes, the orientation of the magnetic field lines and the interaction of plasma with neutrals may play a significant role in seeding irregularities, although many open questions remain regarding cause and effect. The competing physical mechanisms that govern the initiation, growth, and suppression of equatorial plasma bubbles (EPBs) are not well understood. At low latitudes, potential seeding mechanisms (such as gravity waves), tropospheric events (such as lightning flashes), traveling ionospheric disturbances, prompt penetration electric fields, and the disturbance dynamo have been proposed. There are climatological controlling factors, such as orientation of the terminator with respect to magnetic meridian, and variable factors, such as neutral winds and global electric fields.

On many nights, low-density plasma bubbles emerge from the lower F-region ionosphere and rise quickly to altitudes of 1,000 km, often becoming very turbulent and leading to dramatic height versus time intensity variations. Satellite-based communication and navigation may be disrupted, such that predicting these conditions is an important goal of space weather research.

Past missions that have been used to observe the ITM state during scintillation occurrence include Communications/Navigation Outage Forecasting System (C/NOFS), Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC), COSMIC-2, Defense Meteorological Satellite Program (DMSP), GOLD, ICON, Scintillation Observations and Response of the Ionosphere to Electrodynamics (SORTIE), and Swarm. Satellite-based measurements of in situ conditions and associated GNSS loss of lock have played a role in underscoring the space weather import of this question. As an example, Figure D-11 maps the global occurrence of GPS loss of lock for the Swarm A LEO satellite. Combining the satellite observations with ground-based observations has enabled consideration of both the plasma and neutral states during instances of EPBs. Large ground-based facilities, such as Arecibo and Jicamarca, and networks of distributed ionospheric sensors, such as Low-Latitude Ionospheric Sensor Network (LISN), have been key to obtaining these observations.

The relative abundance of scintillation data with even one scintillation receiver, or derivable from a distributed network, has been an impetus for recent initiatives in leveraging data science methods, including artificial intelligence and machine learning. At least one NASA Living With a Star (LWS) Focused Science Team has addressed scintillation-related topics.

One of the challenges with modeling EPBs is the multiple scales and multiple possible phenomena to investigate. There are multiple models that address different possible seeding mechanisms, some that are well equipped to handle global tides and waves, others that model ionospheric plasma, and still others that work at the instability mechanism scales themselves, either modeling the linearized growth rates or directly simulating irregularity development from first principles. Progress has been made in vertically coupling lower atmosphere models to propagate midlatitude convective weather systems up to the thermosphere. These have qualitative similarities to simultaneous traveling ionospheric disturbances (TID) observations, but more cross-model coupling including for different scale sizes is needed to begin to address the seeding mechanism question quantitatively. A developing capability in modeling is emerging bringing multiple models together to cross the scale sizes and boundaries (PSGs 1 and 2). Figure D-12 is an example that points the way: high-resolution models that are one-way coupled (left and middle) bear a striking resemblance to GOLD observations (right).

However, these models are coupled from WACCM-X to SAMI3 (one-way) at present. After adding vertical and multiscale coupling in models, these model outputs then must be further coupled to electromagnetic propagation to show the beginning-to-end connection to scintillation observations. Geospace Environment Model of Ion-Neutral Interactions (GEMINI)+ Satellite-beacon Ionospheric-scintillation Global Model of the upper Atmosphere (SIGMA) modeling is one such example. Further progress is needed in coupling the models, and the question then arises as to whether they will be able to produce enough fidelity to reproduce observations and allow quantitative single comparisons to be made. Because turbulence has elements of a random phenomenon, quantitative measures of significance will need to be developed statistically, which requires many more model outputs than are currently produced, at levels far beyond case studies.

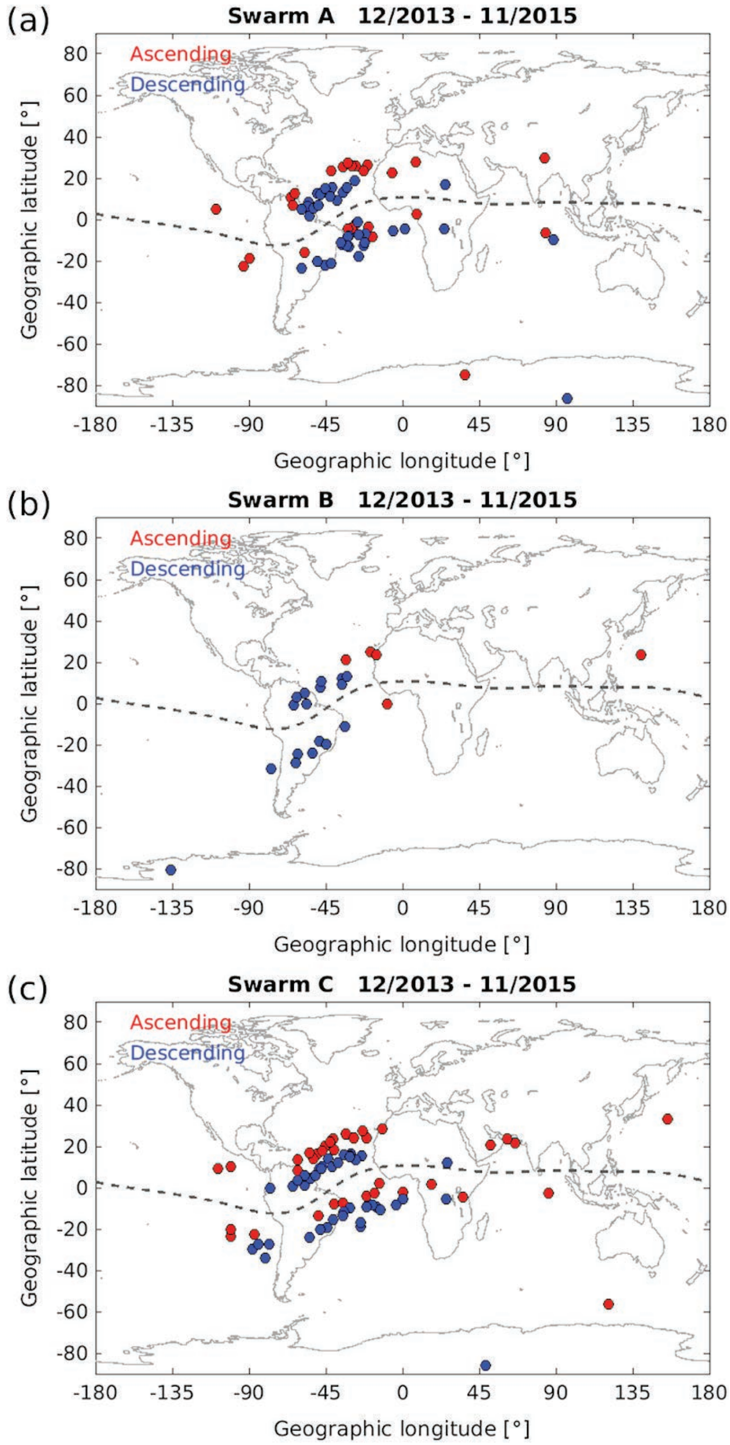


FIGURE D-11 The global distribution of Global Positioning System (GPS) signal total interruption for all channels observed by the Swarm A satellite. Ascending and descending orbital arcs are marked with red and blue, respectively, and the dashed line denotes the magnetic equator.
SOURCE: Xiong et al. (2016).

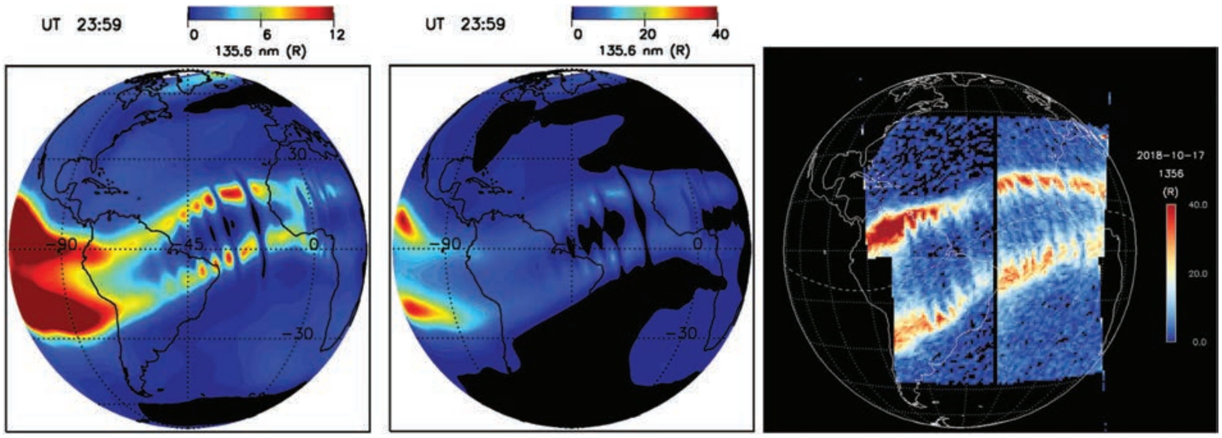


FIGURE D-12 Comparison of 135.6 nm emissions from a high-resolution SAMI3/WACCM-X one-way coupled simulation for a March low solar activity condition (*Left and Middle Panels*) and GOLD emission data (*Right Panel*) observed from geosynchronous orbit.
SOURCES: (*Left and Middle Panels*) Huba and Liu (2020); (*Right Panel*) Eastes et al. (2019), https://doi.org/10.1029/2019GL084199. CC BY.

While progress has been made in data assimilation at global scales in the past decade, including the quantification of uncertainties, none of these assimilative methods operate at scintillation scales. There are no first-principles instability models that can assimilate scintillation measurements. For existing data assimilation techniques, incorporating new measurements from the GDC, DYNAMIC, and AWE missions will help connect the coupling mechanisms. The ENLoTIS (European Space Agency [ESA]/NASA Lower Thermosphere–Ionosphere Science) mission concept could provide comprehensive EPB dynamic features along with their driver measurements, combined with data from small satellite platforms. In particular, continued observation of EPBs, their possible triggering parameters, and the resultant scintillations must be made in order to feed quantitative assimilation solutions for a case-by-case mapping that will unlock progress in cause and effect understanding.

Priority Science Goal 3, Objective 3.2: Quantify the Relative Significance of Competing Drivers of Day-to-Day Variability in the ITM System

Day-to-day variability in the ITM system can arise from changes in several factors. Many competing drivers of the observed variability in the neutral wind field in particular have been identified, including auroral energy deposition, electric fields, gravity wave breaking, nonlinear interactions among various wave types, and ion-neutral coupling. Currently, the predictability of the seasonal, diurnal, and solar cycle variability of neutral winds is poorly characterized because the data sets are too sparse, and the model drivers are not adequately characterized. In addition, the effect of preconditioning on these drivers and the observed mesoscale variability is not well understood.

An ultimate aim is to develop physics-based and assimilative models to accurately predict ITM day-to-day variability (weather) far in advance, similar to tropospheric forecast models. The neutral wind field in the mesosphere and thermosphere exhibits significant temporal variability on timescales of hours to days, even in the quietest geomagnetic conditions. Figure D-13 depicts output from a high-resolution global model simulation that illustrates the type of variability in vertical winds that is caused by orography and tropical cyclones. This variability results in day-to-day modification of the ionosphere electron density. In contrast to tropospheric weather forecasting capability, current physics-based and assimilative models are unable to accurately predict ITM weather conditions.

Recent ITM missions were successful in exploring specific processes. ICON investigated various drivers (composition, neutral winds, dynamo electric fields) and their relative importance to ionospheric variability, but only on large spatial (global) and temporal (seasonal) scales. TIMED characterized the MLT energy budget and quantified contributions to thermospheric cooling.

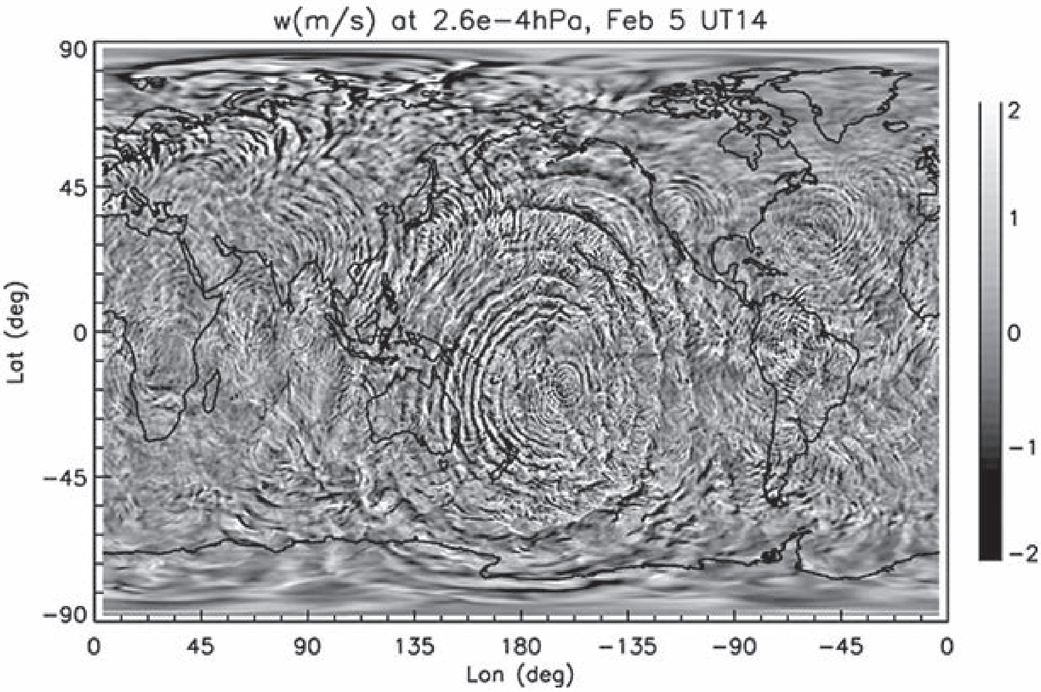


FIGURE D-13 Output from a high-resolution global l simulation using the Whole Atmosphere Community Climate Model (WACCM) that illustrates the type of variability in vertical winds that is caused by orography and tropical cyclones. Simulated vertical winds at the 2.6×10^{-4} hPa model pressure level (~100 km) on February 5 at 14:00 UT. The resolution of this model is ~0.25° in the horizontal and 0.1 scale height in the vertical.
SOURCE: Liu et al. (2014).

GDC and DYNAMIC are well suited to address important PSG 3 problems through their planned strategic coordination. Through simultaneous operation, they will explore elements of system-level quantification, including the origins and impacts of day-to-day variability. Ground-based observations from IS radars, ionosondes, SuperDARN HF convection radars, neutral airglow Fabry-Pérot instruments, all-sky imagers, and related network efforts also will continue to provide important local and regional/continental scale measurements of ITM variability in a fixed local time sensor view, especially when coordinated with the complementary picture determined from in situ satellite platforms.

Most past and current modeling efforts have insufficiently addressed model output uncertainties and their sensitivity to external (e.g., solar EUV, auroral precipitation) and internal parameters (e.g., reaction rates, cross sections). The recent NSF Space Weather Quantification of Uncertainties program is aimed at creating space weather models with quantifiable predictive capabilities through advancing modeling approaches and the proper treatment of observational inputs.

Some instruments provide inherent quantification of uncertainty on the retrieved state parameters, but often the error analysis is ad hoc. Results are often reported without appropriate treatment of either measurement/retrieval uncertainty or systematic bias associated with physical assumptions of the retrieval approach. The need for robust uncertainty quantification (UQ) has been established in the applications community (e.g., space weather forecasting), but UQ is just as important for scientific understanding of ITM system variability.

Priority Science Goal 3, Objective 3.3: Quantify the Most Salient Factors Governing the Global ITM Response During and Following Geomagnetic Activity

The ITM response to geomagnetic storms has been a topic of study for several decades, and substantial recent progress in understanding individual mechanisms has been made by missions such as TIMED, GOLD, and ICON, as well as by ground-based assets such as IS radars, LiDARs, and optical observations. Many competing drivers contribute to the ITM response to magnetic storms, including neutral winds, electric fields, energetic particle precipitation, neutral temperature, and composition (O, N_2, and NO) changes. However, the relative importance of various controlling mechanisms of the system behavior is not well established. Quantifying the relative importance of these factors is crucial to understanding the storm-induced changes in the ITM system.

For example, both ICON and GOLD satellite observations have revealed large effects in multiple ionospheric and thermospheric parameters, which exhibit significant spatial structure even at midlatitudes, following even very weak storms (see Figure D-14). The patchy nature of the midlatitude thermosphere composition response to a storm illustrates why predicting magnetic storm effects is difficult and why global-scale sensing is so important. Progress has been hampered by insufficient temporal and spatial resolution of the observations. Numerical advances such as whole geospace and assimilative models are developing quickly and will be excellent tools for further progress when combined with appropriate data sources.

A major impediment to a better understanding of ITM behavior during and after a storm event is that they rarely have similar characteristics. The lack of good storm indices and the necessary averaging of the thermosphere response data help explain why the Naval Research Laboratory Mass Spectrometer and IS Radar Exosphere (NRLMSISE-00) empirical model is much less reliable during disturbed times than during quiet times. Likewise, quantifying the auroral energy input with its high temporal and spatial variability is a key problem for physics-based models. Another uncertainty is the vibrational distribution of N_2, which has a major effect on the ionosphere density by increasing the O^+ loss rate during elevated levels of magnetic and solar activity. Although the vibrational state of N_2 can be well modeled, its calculation is very computer intensive and has not yet been included in global models. This can lead to overestimation of the F-region electron density by a factor of 2. Resolving these difficulties to further advance modeling capability needs to incorporate simultaneous images of both north and south auroral regions, coupled with in situ measurements and comprehensive ground-based measurements in both hemispheres. Such multielement analysis approaches have proved quite productive in the recent past for similar challenges; for example, a major improvement in storm modeling was achieved by including conductance patterns derived from the Polar UVI auroral images together with ground magnetic perturbations that include mesoscale structure.

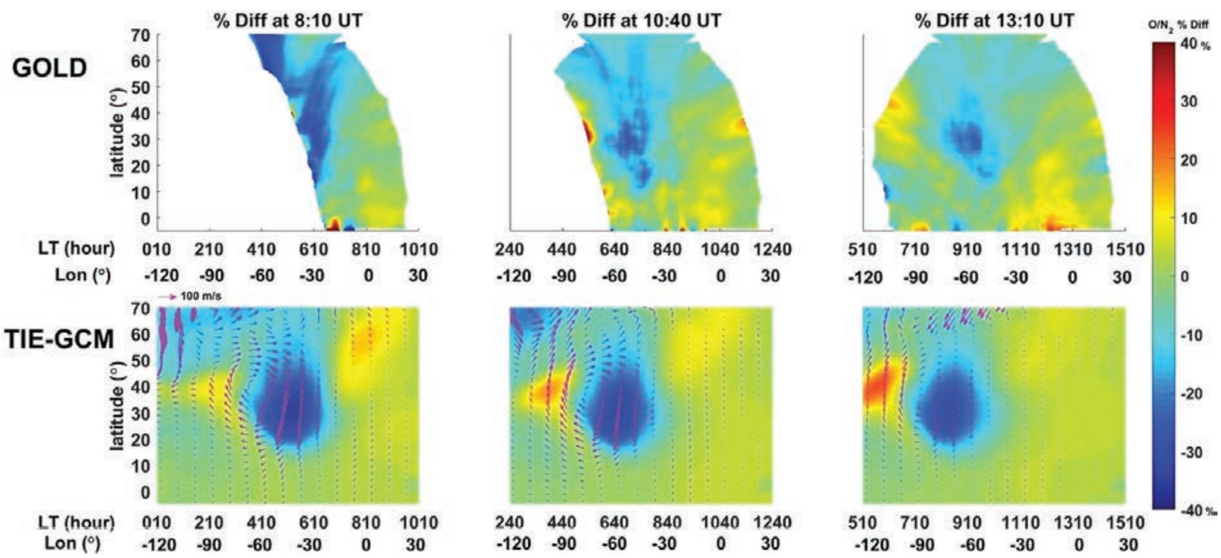


FIGURE D-14 Latitude–longitude distribution of the percentage differences between day of the year (DOY) 156 and 154 of 2019 in (*First Row*) GOLD observations and (*Second Row*) Thermosphere–Ionosphere–Electrodynamics General Circulation Model (TIE-GCM) simulations with neutral wind differences vectors (pink) at pressure level –1.375 (~160 km). The longitude and the corresponding local time are given as the D-axis. Large and long-lived depletions occur in O/N_2 ratios even during weak geomagnetic activity.
SOURCE: Cai et al. (2020).

Priority Science Goal 3, Objective 3.4: Quantify the Origin of Interhemispheric Asymmetries in Geospace and Their Effects on the ITM System

Interhemispheric asymmetry in current circuits, particle precipitation, and electron density is now understood to be a common feature of global and mesoscale ITM structure and variability, and Figure D-15 illustrates an example of this phenomenon. Conjugate asymmetries are believed to arise from both intrinsic ITM factors (e.g., the geomagnetic field, ionospheric conductivity, atmospheric waves) and external factors (e.g., the solar wind and magnetospheric forcing). Investigating the nature and origin of interhemispheric asymmetries in global and mesoscale structures offers critical tests of our understanding of the ITM system response to competing drivers.

The magnetosphere–ionosphere–thermosphere–mesosphere system regulates Earth's global current circuit, highlighting the critical importance of ionospheric conductivity. A number of ITM processes that govern structure in conductivity (Joule heating, transport, precipitation, composition) compete to regulate, for instance, the substorm cycle for different situations. How the global current circuit influences ITM system behavior, and how the ITM system regulates the global current circuit, are the net results of the balance of a number of competing processes. A complete understanding of this ITM system regulation will be valuable through its ability to explain and predict the effects of interhemispheric asymmetries (and symmetries/magnetic conjugacy) in energetic particle precipitation, currents, and flows.

Many existing resources have contributed to the understanding of these questions so far. Ad hoc conjunctions of ground-based auroral imagery arrays (THEMIS-GBO) with satellite data (ESA-Swarm, DMSP) and radar data (PFISR, RISR, EISCAT) have supported investigations of storm-time ITM system dynamics in high-latitude regions, although primarily confined to the northern hemisphere. Meanwhile, magnetometer chains across Canada, Alaska, and Scandinavia provide models with continuous and distributed data constraints needed for a variety of studies.

Directed research programs have also focused on some of these questions. For example, NSF CEDAR Grand Challenge studies have included "Interhemispheric Asymmetries (IHA) and Impact on the Global I-T System" (2023), "Multi-Scale I-T System Dynamics" (2021), and "The High Latitude Geospace System" (2016). Recently, assimilative tools such as LOMPE allow the aggregation of heterogeneous data sets into maps of information that can be used to drive models. Larger-scale similar tools such as Assimilative Mapping of Ionosphere Electrodynamics (AMIE) have significantly contributed to these studies.

However, much of this recent progress has relied on ad hoc conjunctions and collaborations. With dedicated and strategic coordination of new and existing measurement and modeling assets, the community is poised for much larger advances toward this important science priority.

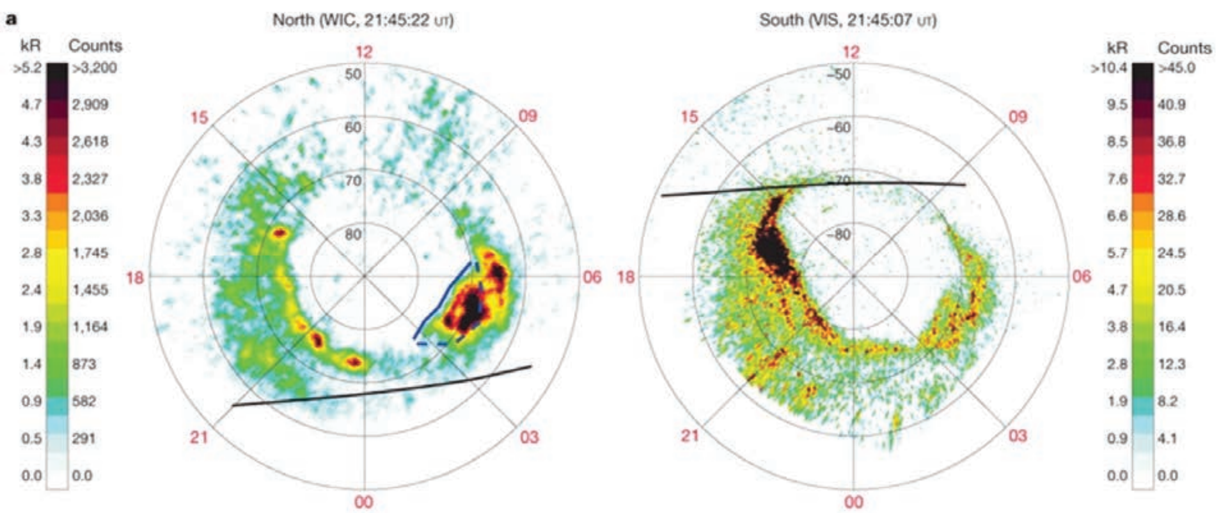


FIGURE D-15 IMAGE (north) and Polar (south) interhemispheric asymmetries (IHA) example.
SOURCE: K.M. Laundal and N. Østgaard, 2009, "Asymmetric Auroral Intensities in the Earth's Northern and Southern Hemispheres," *Nature* 460:491–493, https://doi.org/10.1038/nature08154, reproduced with permission from SNCSC.

Synopsis of Priority Science Goal 3

The efforts of PSG 1 and PSG 2 will identify important physical ITM processes both internally and across system boundaries under a range of geophysical conditions. However, it is also essential that the relative significance of these processes is understood within these ranges, including preconditioning effects, to solidify understanding of which system pathways compete and contribute to dynamic control and how these pathways change roles across variable conditions. Such knowledge is foundational to efforts to understand, to model, and ultimately to predict the nature and variety of ITM dynamics. It also fosters a more complete understanding of the ITM system through identification of fundamental causative mechanisms along with baseline behavior, sensitivity to external drivers, and emergent processes. Optimal study of ITM behavior and the identification of relative significance and consequences of competing physical system processes in the next decade thus involves the panel's identified science objectives, summarized here:

1. Quantify the relative roles of preconditioning and seeding mechanisms in controlling the emergence and evolution of ionospheric irregularities.
2. Quantify the relative significance of competing drivers of day-to-day variability in the ITM system.
3. Quantify the most salient factors governing the global ITM response during and following geomagnetic activity.
4. Quantify the origin of interhemispheric asymmetries in geospace and their effects on the ITM system.

D.3.4 Priority Science Goal 4: How Does Earth's ITM System Respond to Persistent Changes in the Geospace Environment?

As illustrated by many of the preceding examples, Earth's ITM system is highly dynamic, capable of simultaneously exhibiting day-to-day variability, large transient responses to impulsive perturbations, and climatological periodicities on diurnal, seasonal, and solar cycle timescales. Over the past few decades, it has become clear that the ITM is also undergoing secular evolution on much longer timescales. Several key ITM state parameters, such as total atmospheric mass density and temperature, have been observed to be slowly but significantly deviating from their historical ranges associated with sporadic and climatological variability. Physics-based modeling suggests that these changes are occurring primarily in response to anthropogenic increases in atmospheric CO_2 and methane. However, as described further in the section "Priority Science Goal 4, Objective 4.2," the response of the ITM system to Earth's climate evolution is highly complex, involving not only temperature and density variations but also changes in mesospheric chemistry, gravity wave generation, atmospheric circulation, and more.

In the next decade, new anthropogenic changes in the ITM are likely to occur in response to the planned deployment of mega-constellations of satellites as well as potential geoengineering initiatives for radiation management, such as stratospheric aerosol injection. Meanwhile, the ITM is strongly influenced by persistent changes in its natural system drivers, such as the accelerating reconfiguration of Earth's intrinsic magnetic field or extended periods of unusually weak or strong solar activity and irradiance (see the section "Priority Science Goal 4, Objective 4.1"). Although current trends appear to be gradual, complex dynamical systems like the ITM can experience large, abrupt, and often irreversible transitions between stable dynamical states when driven beyond critical thresholds (tipping points). Earth's global climate system is widely considered to be approaching numerous tipping points in the coming decades, and dynamical state transitions can occur in response to even small changes in tightly coupled system drivers. Understanding the nature, origin, and effects of the ITM response—whether slow or sudden—to persistent changes in its various drivers—whether natural or anthropogenic—is a critical aspect of understanding Earth's ITM as a coupled dynamical system.

Advancing current understanding of Earth's upper atmospheric state evolution is the focus of the ITM panel's PSG 4 for the coming decade. This priority builds on the 2013 decadal survey, specifically AIMI Science Goal 5 ("How is our planetary environment changing over multidecadal scales, and what are the underlying causes?"), which explicitly recognized the fundamental importance of geospace evolution. PSG 4 also builds on "CEDAR: A New Dimension," whose Strategic Thrust 3 set forth a mission "To understand and predict evolutionary change in the geospace system and the implications for Earth and other planetary systems" (CEDAR 2011). Much progress has been made toward these strategic goals in the past decade, through both rigorous analysis of historical ITM measurements as well as whole atmosphere numerical simulations driven by extreme conditions.

However, current assessments of secular ITM trends are based primarily on uncoordinated data of opportunity rather than systematic and strategic investigation. Moreover, the past decade's focus on slowly evolving trends overlooks the potential for relatively rapid transitions in either ITM drivers or its response. Identifying the limits of dynamical ITM stability and assessing the impacts of potential tipping points are particularly unexplored and important areas of research. The following sections describe specific scientific objectives identified by the panel within PSG 4 for which significant progress can be achieved in the next decade.

Priority Science Goal 4, Objective 4.1: Determine How the ITM Is Influenced by Slowly Evolving Trends in Its Natural System Drivers

The ITM system is driven predominantly by the conditions of the natural environment in which it is embedded—namely, solar radiation controls ionization and heating; the interaction of the solar wind and interplanetary magnetic field with the magnetosphere generates high-latitude ionospheric current systems and induces plasma transport; and these, together with lower atmospheric conditions, influence atmospheric chemistry and dynamics. While these natural drivers exhibit both sporadic variability and climatological periodicities, some also evolve on decades-long timescales, with large effects on the quasi-equilibrium state of the ITM system.

A well-known example of long-term changes in natural ITM forcing is the unusually deep solar minima that occurred in 2009 and 2019, along with the muted solar maximum in between. Continuing a trend of weakening solar activity seen over the past four solar cycles (Figure D-16), Solar Cycle 24 was the weakest cycle in more than 100 years, in addition to being relatively short at only 10 years. Historically, relatively weak solar cycles are rare but not unprecedented, even in series (the Dalton Minimum). Deep solar minima are more common, and a very long period of extreme dormancy (the Maunder Minimum) occurred over the 400-year sunspot data record. Solar Cycle 25, which is expected to peak in 2025, is already greatly exceeding early predictions of persistent weakness, such that the recent secular trend of decreasing solar activity may be abating.

Regardless of future solar conditions, the sustained decrease in solar output during the past decade is a rare "natural experiment," which has presented the opportunity to elucidate the response of the ITM to a key system driver: solar EUV irradiance. Both the Solar EUV Experiment (SEE) and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instruments onboard NASA'S TIMED mission have been operating since 2002, far beyond their nominal mission lifetime. This serendipitous data revealed that the low solar flux during Solar Cycle 24 had a profound impact on the ITM state. For example, radiated energy from NO and CO_2 were measured to be only 50 percent and 73 percent, respectively, of the average emission of the five prior solar cycles dating back to 1954, indicative of a significantly cooler thermosphere (Mlynczak et al. 2019).

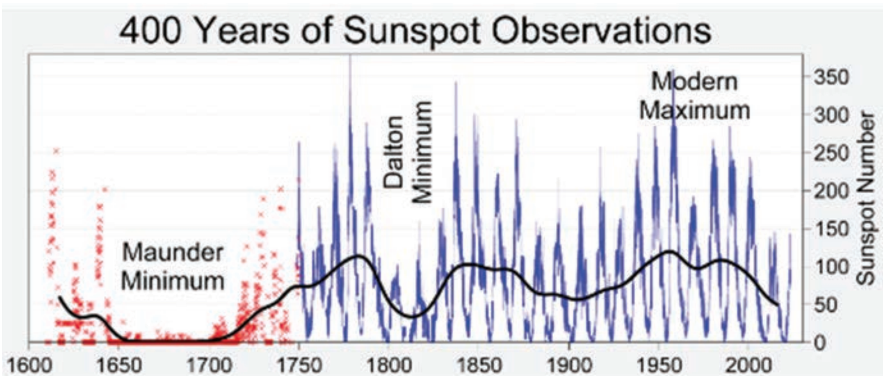


FIGURE D-16 Observed sunspot numbers, proxies for solar activity, exhibit cyclical 11-year periodicity as well as long-lived state transitions.
SOURCE: Robert A. Rohde, "Sunspot Numbers," Global Warming Art, https://commons.wikimedia.org/wiki/File:Sunspot_Numbers.png. CC BY-SA 3.0.

Another slowly varying ITM system driver is Earth's intrinsic magnetic field geometry, which evolves continuously owing to motion of the planet's molten core. Since 1990, the north magnetic pole has been migrating at an increased speed relative to its rate over most of the past century and now averages more than 40 km/year (Figure D-17). Because the migration of the south magnetic pole is considerably slower, the global configuration of the geomagnetic field away from the poles is also changing, as demonstrated by the sustained drift of magnetic footprints at midlatitudes (e.g., L shell decline of 0.5 at Millstone Hill from 1983–2023). This evolution has a significant impact on ITM electrodynamics and ion-neutral coupling on global scales, and, accordingly, ground-based instruments at fixed geographic locations are observing an increasingly evolving plasma environment. The natural trend also has practical impacts on space-based assets that transit the South Atlantic Anomaly (SAA), a localized region where the global geomagnetic field intensity is smallest. Since 2020, the SAA has weakened further (by 80 nT at sea level), moved westward (by 70 km at sea level), and expanded in size (by 5 percent), such that energetic particles from Earth's radiation belt can penetrate farther into the upper atmosphere, posing increased risk of damage to satellites in low Earth orbit.

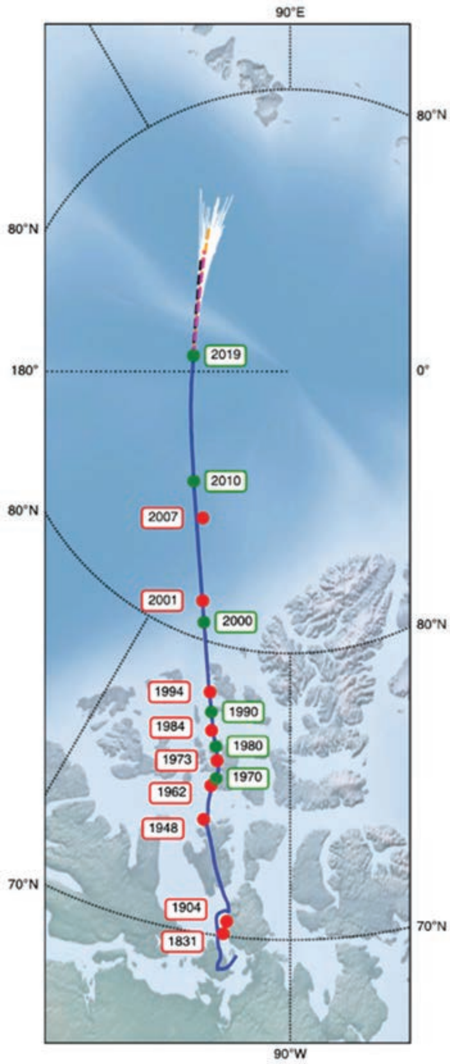


FIGURE D-17 Migration of the north magnetic pole over the past 200 years.
SOURCE: P.W. Livermore, C.C. Finlay, and M. Bayliff, 2020, "Recent North Magnetic Pole Acceleration Towards Siberia Caused by Flux Lobe Elongation," *Nature Geoscience* 13:387–391, https://www.nature.com/articles/s41561-020-0570-9, reproduced with permission from SNCSC.

Addressing PSG 4.1 in the next decade will not only advance understanding of the ITM as a naturally evolving system but will also enable optimization of the design, deployment, and operation of current and future sensors and platforms affected by this evolution.

Priority Science Goal 4, Objective 4.2: Determine How the ITM Is Influenced by Anthropogenic Changes in Atmospheric Composition

In addition to its strong response to the slow evolution of the natural drivers described earlier, Earth's ITM system is highly sensitive to changes in atmospheric composition resulting from human activity. A well-known example is the sustained decrease in thermospheric mass density, of ~1 to ~10 percent per decade depending on altitude, as inferred from the effects of aerodynamic drag on satellite trajectories in low Earth orbit. These data are generally consistent with numerous modeling studies of the ITM response to anthropogenic increases in atmospheric CO_2, whose optically thin infrared emission above the stratosphere is predicted to cool the upper atmosphere, resulting in its corresponding contraction and density decrease at a given height.

In support of this prediction, strong ion temperature decreases in the F-region ionosphere have been observed consistently over a wide range of geomagnetic latitudes by several IS radars, whose uniquely robust parameter retrieval capabilities and decades-long baselines of available data are well suited for unambiguous trend detection. However, the observed ion temperature decrease of ~50–100 K/decade is substantially larger than the magnitude of neutral atmospheric cooling predicted by current models, and more work is needed to understand the complex chemical and electrodynamical interactions by which the ITM mediates its response to this anthropogenic trend.

Like CO_2, atmospheric methane (CH_4) is also increasing as a result of modern human activity, and the rate of increase has accelerated significantly over the past decade (see Figure D-18). Because it is a potent greenhouse gas, increases in atmospheric CH_4 increase surface temperatures, which in turn accelerates permafrost melting and its associated release of additional CH_4 in a powerful feedback loop. Late 2023 marked the first time in recorded history that the daily-averaged global surface temperature breached 2°C above the preindustrial (1850–1900) temperature baseline, and the annually averaged global surface temperature is on track to exceed the 1.5°C anomaly threshold within the next few years. Higher surface temperatures drive enhanced surface water evaporation, thereby increasing water vapor concentrations alongside CH_4 in the stratosphere and mesosphere. The sustained increase in water vapor abundance and decrease in mesospheric temperature may be associated with the unexpected increase in the occurrence frequency and spatial distribution of noctilucent clouds observed by the recently decommissioned AIM mission.

Over the past decade, climate models capable of simulating centennial-scale changes in the lower atmosphere have been extended upward to cover the ITM (e.g., WACCM-X, Hamburg Model of the Neutral and Ionized Atmosphere [HAMMONIA], and the Canadian Middle Atmosphere Model [CMAM]). Modeling studies have revealed that this significant change in ITM composition affects ozone chemistry as well as atomic hydrogen production and escape, which in turn affect the structure of the exosphere and its charge-exchange coupling to ions in the plasmasphere and magnetospheric ring current. Furthermore, ongoing and expected changes in lower atmosphere temperature, circulation, and weather patterns, including increased tropospheric storm frequency and intensity, are expected to alter the generation of gravity waves and wave-driven circulation in the ITM relative to present-day conditions.

Intentional geoengineering efforts, with the aim of mitigating some of the harmful effects of anthropogenic increases in greenhouse gas concentrations, may themselves induce persistent changes in the ITM. For example, solar radiation management strategies, such as stratospheric injection of sulfur dioxide (SO_2), have received increased attention over the past decade as a potential means to temporarily increase Earth's albedo and thereby cool the troposphere, much as natural volcanic eruptions have done in the past. However, the amount of stratospheric aerosols needed to impact surface temperature is highly uncertain, and potential impacts on other Earth systems, including the ITM, are currently unknown. Although arguments of moral hazard in light of these uncertainties have limited major geoengineering efforts to date, the first SO_2 release experiments were conducted in early 2023, and interest in solar radiation management approaches is likely to grow as Earth's surface continues to warm in the coming decades.

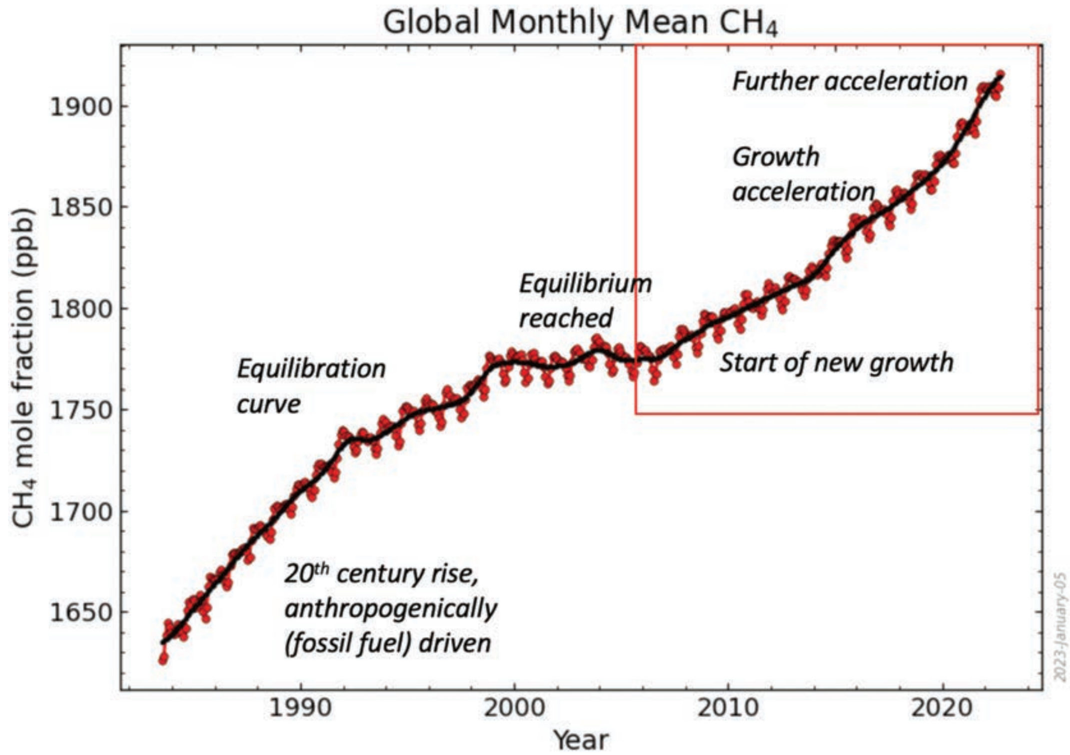


FIGURE D-18 Trend in atmospheric methane (CH_4).
SOURCE: Nesbitt et al. (2023), https://doi.org/10.1029/2023GB007875. CC BY.

Unintentional anthropogenic changes in ITM composition are also anticipated over the next decade, owing mainly to the ongoing and future deployment of "mega-constellations" of commercial communications satellites. From 2019 to 2021, the total number of active and defunct satellites in low Earth orbit increased by 50 percent, to more than 5,000, and that number is expected to increase to more than 50,000 in the next decade. The atmospheric reentry of deorbiting satellites at the end of their operational lifetime deposits fine particulates of many species of metal atoms throughout the upper atmosphere—in particular, the expected deposition of aluminum from the deorbit of planned mega-constellations will greatly exceed (by more than 400 percent) the aluminum deposition rate by meteoroids. Such a large increase in atmospheric metal concentration may have a significant impact on the chemistry of the middle atmosphere and on Earth's albedo. Furthermore, the current rate of rocket launches will increase significantly to support the deployment and continual renewal of satellite mega-constellations. By-products from rocket propulsion also affect atmospheric chemistry by depleting stratospheric ozone, inducing direct radiative forcing, and providing potential catalytic agents which can change chemical rates and pathways in unexpected ways.

Owing to these significant and persistent anthropogenic trends, the next decade is likely to be characterized by unprecedented external and internal forcing on ITM composition, chemistry, and dynamics. PSG 4.2 is focused on advancing the understanding of these important effects in support of improved prediction and potential mitigation efforts.

Priority Science Goal 4, Objective 4.3: Determine Which Aspects of the ITM State Are Most Sensitive to Persistent Changes in Its System Drivers

As described earlier, several key ITM system drivers have sustained significant secular evolution over the past several decades, and these trends are widely expected to continue or even accelerate in the decades to come.

Observational evidence that the ITM responds strongly to such changes is compelling. However, in contrast to lower atmospheric state characterization, which benefits from the availability of much longer, continuous, and globally distributed data series, suitably long baselines of well-calibrated ITM state parameter measurements are notoriously sparse. Current empirical knowledge of long-term ITM evolution is based primarily on either height-resolved parameters at very few geographic locations (e.g., precise and comprehensive ionospheric specification by IS radars) or globally distributed parameters over a limited altitude range (e.g., MLT temperature and composition by TIMED/SABER or total neutral mass density via satellite drag). Owing to the uncoordinated and inherently opportunistic nature of existing ITM data series, available observations do not necessarily reflect the most salient features of the ITM response to secular driver evolution and thus do not provide sufficient constraints on the critically important effects of these trends.

Physics-based modeling is therefore a vital tool for advancing understanding of the nature and origin of secular ITM variability. A major challenge in understanding the ITM response is the nonlinear mixing of multiple drivers, such as the persistent decrease in average solar flux over Solar Cycle 24, which occurred simultaneously with an increase in atmospheric CO_2 abundance. The 11-year solar cycle has a very strong influence on the ITM system, and removal of solar cycle effects from observational data series, in order to isolate longer-term trends, is highly challenging. Model simulations enable vital investigations of co-occurring and potentially counteracting trends in ITM drivers independently, while also supporting the identification of ITM observables that exhibit the most sensitive response to those changes. With improved knowledge of ITM sensitivity derived from modeling results, future deployments of both ground- and space-based sensors can then be optimized for their salience in addressing PSG 4.

Priority Science Goal 4, Objective 4.4: Determine the Fundamental Physical Limitations on the Dynamic Stability of the ITM

Understanding of the ITM is based on a relatively short observational record, weighted heavily to the satellite era. Unlike the tropospheric climate record, which extends for millennia through the use of proxy data, the short record of ITM structure and dynamics does not permit us to straightforwardly estimate the likelihood of ITM climate shifts. The state of the ITM uniquely depends on the interaction of dynamics and chemistry and with the atmospheric layers with which it is coupled. Observing and modeling the balance between these influences has led to a system we continue to understand better. However, should any one of these influences undergo a major step change that lies outside the known climate record variability, there is little capability at present to predict how the coupled ITM system might respond. A particularly important open question is whether the ITM could undergo a transition to a new and potentially radically different dynamical state. For example, it is established that the mesosphere and lower thermosphere region departs from radiative equilibrium owing to dissipation of atmospheric gravity waves, but how will this region be impacted if the sources of these waves change following the troposphere, potentially crossing a climatic tipping point?

Ultimately, the panel finds that more research is needed to better understand the stability of the physical state of the ITM in response to step changes such as the loss of the Greenland Ice Sheet, changes in the frequency or intensity of the hurricanes, changes in stratospheric wind patterns, likelihood of Southern Hemisphere stratospheric warmings, or, as discussed above, the frequency of deployment of mega-constellations. This research necessarily will rely heavily on model simulations, which were developed based on our existing observational record and incorporate parameterizations tuned for today's climate. As such, current models will need to be evaluated in terms of their ability to produce radically different climate states.

Synopsis of Priority Science Goal 4

Together, PSGs 1, 2, and 3 aim to advance understanding of the present-day ITM system and its day-to-day, transient, and climatological variability. PGS 4 complements these goals through its focus on ITM system evolution into the future, which is being driven by ongoing and accelerating changes in key system drivers, including the reconfiguration of the geomagnetic field as well as sustained and accelerating increases in atmospheric CO_2, CH_4, H_2O, and particulate abundance. In addition to leveraging and expanding existing observational data series that have suitably long baselines to support secular trend detection, addressing PSG 4 also benefits from comprehensive whole atmosphere modeling as a means to assess the limits of dynamical ITM stability under extreme conditions as well as the ITM system's sensitivity to realistic expectations of driver evolution. A crucial component of PSG 4 is to identify thresholds, or tipping points, beyond which the ITM may experience relatively rapid transitions between quasi-stable dynamical states. Such tipping points are known to exist in Earth's climate system as a whole, and current data suggests that such thresholds may be reached in the near future. Understanding how the ITM is likely to respond to these changes, whether slowly or abruptly, is vital for the development of a strategy to both monitor this evolution observationally as well as mitigate the effects of these changes on numerous technological assets. The panel's identified science objectives in support of PSG 4 are summarized here:

1. Determine how the ITM is influenced by slowly evolving trends in its natural system drivers.
2. Determine how the ITM is influenced by anthropogenic changes in atmospheric composition.
3. Determine which aspects of the ITM system are most sensitive to persistent changes in its system drivers.
4. Determine the fundamental physical limitations on physical stability of the ITM.

D.4 LONG-TERM SCIENCE GOAL: HOW DO ITM SYSTEMS OPERATE ON OTHER WORLDS WITH VERY DIFFERENT CHARACTERISTICS AND PHYSICAL DRIVERS?

Because of its accessibility and societal importance, ITM science has concentrated on the study of Earth's upper atmosphere. However, a complete understanding of the physical principles that control ITM systems benefits from knowledge of other atmospheres with a range of different physical characteristics and system drivers. The key differences that govern the nature and variability of the upper atmospheres of other planets include

- Proximity to the sun and solar wind intensity;
- Atmospheric composition and dynamics;
- Planetary mass and rotation speed; and
- The magnetic fields and plasmas in which they are embedded.

Measuring the ITM states of other solar system planets and their energy inputs would significantly advance a general understanding of the fundamental physics and chemistry of upper atmospheres, particularly their transient variability and evolution. This knowledge will in turn allow more accurate modeling of the expected conditions in the ITM systems of exoplanets, for which there is little data.

D.4.1 Long-Term Science Goal, Objective L.1: Determine How the Intense Auroral Energy Input to Jupiter's Thermosphere Drives Its Global Dynamics, Composition, and Ionization

Jupiter's auroral energy input is 50–100 times greater than its global solar EUV energy input, and the intense auroral heating is expected to have a major influence on the global thermosphere circulation and dynamics. Auroral currents drive a supersonic equatorward expansion that has yet to be fully characterized, understood, and modeled. Although the strong Coriolis forces resulting from the rapid rotation of the planet should confine the auroral energy to the polar regions, global Jovian exospheric temperature unexpectedly exceeds 1,000 K. This phenomenon is often referred to as the giant planet "energy crisis," but it is ultimately a crisis in understanding that must be resolved if researchers are to understand fundamental ITM systems in general and by extension those of giant exoplanets outside the solar system. Prior space missions (Juno, New Horizons, Cassini, Galileo, and the Voyagers) and future missions (Europa Clipper and Jupiter Icy Moons Explorer [JUICE]) have returned or will return valuable data on the Jovian magnetosphere, and both Earth-orbiting and ground-based telescopes have studied the Jovian aurora and ITM. Observations of the Jovian aurora, plasma torus, and thermosphere/ionosphere would measure the response of its ITM system to both external and internal drivers and provide the data needed to test models for the upper atmosphere energetics and dynamics. Jupiter is also an excellent example of a giant exoplanet-like object that is close enough to study in situ.

D.4.2 Long-Term Science Goal, Objective L.2: Determine How the Solar Wind and EUV Flux Drives the Thermosphere and Ionosphere of Venus and Mars and How These Inputs Govern Atmospheric Escape

The thermosphere and mesosphere of Mars are highly dynamic, with strong tides, gravity waves, and altitude structures that change on timescales of hours. These phenomena are largely driven by upward propagating waves generated by the circulation in the lower atmosphere. There is also a strong seasonal variation that is mainly driven by the changing distance from the Sun, which can lead to a 50 percent change in solar UV irradiance. Near perihelion, strong dust storms in southern summer alter the heating and dynamics of the upper atmosphere. Thus, Mars presents an ITM system in which conditions vary with a greater magnitude and on shorter timescales than on Earth. In the past decade, the NASA Mars Atmosphere and Volatile EvolutioN (MAVEN), ESA Mars Express, and Trace Gas Orbiter missions have gathered data on the middle and upper atmospheric regions; however, no previous mission has measured the time series of the solar inputs and planetary thermosphere/ionosphere reactions for Mars at the temporal and spatial resolution needed to establish cause and effect.

In contrast to both Mars and Earth, the ITM system of Venus appears relatively stable. The very slow rotation provides long times for reactions to take place, which leads to an ionosphere that is close to the ideal for models of a solar-driven system. The thermosphere and mesosphere lie above a very thick, heavy, and relatively stable lower atmosphere that contributes to its low variability. Venus is thought to have the most extreme atmospheric escape of any terrestrial planet. However, Venus remains relatively sparsely studied, with the 1978–1992 Pioneer Venus Orbiter being NASA's only dedicated mission to Venus. Although the Parker Solar Probe has conducted 7 flybys of Venus to date, with another 22 planned in the next decade, no previous investigation has obtained key measurements of the time series of solar inputs and planetary thermosphere/ionosphere reactions coincidentally with observations of the ITM response to those inputs. Important questions remain about what processes control atmospheric escape and how small-scale waves contribute to the super-rotation of the upper atmosphere.

D.4.3 Long-Term Science Goal, Objective L.3: Determine How ITM Processes Influence Exoplanet Habitability

The habitability of an exoplanet depends critically on the output of its host star and its response to that output. This interaction occurs throughout a planet's atmosphere, and key phenomena occur in the ITM region that likely determine at what point in its lifetime a planet might be habitable and for how long. For example, the likelihood that a planet can retain an atmosphere against gravitational escape and ion outflow depends significantly on the composition and temperature of ion and neutral constituents and on their charge exchange interactions.

Knowledge of the ITM characteristics of exoplanets today is based on a thin data set derived from telescopic observations, largely of planet transit light-curves and their spectra. These data are then compared with our understanding of the ITM systems from different planets in our solar system and modeled based on physical principles. Advances in understanding the evolution and escape of exoplanet atmospheres requires (1) higher-quality observations, now taking place with large telescopes; (2) improving the knowledge of the ITM systems of the other planets in our solar system (see Sections D.3.1 and D.3.2 above); and (3) development of physics-based numerical models and their data-driven verification. This latter approach would greatly benefit from collaboration between different research groups (i.e., Earth and other planetary researchers) and disciplines. Knowledge of Earth's auroral processes can also be profitably applied to exoplanet studies, through for example radio-based techniques to remotely detect the potential presence of a magnetosphere through detection of bright and coherent auroral kilometric radiation along with other similar plasma wave-driven emission features.

D.5 EMERGING OPPORTUNITIES

The past decade has been marked by the rapid technological development of small satellite platforms, development of new launch vehicles, and the entrance of many innovative spaceflight companies. Together with the development of cutting-edge data science tools, agile cloud computing, and the overall expansion of related fields, these advances produce a fertile landscape for innovation in the near future. Only through the utilization of the emerging opportunities described below will the next decade's ITM PSGs be fully addressed.

D.5.1 Emerging Opportunity 1: Harness the Growing Deployment of Globally Distributed Commercial, International, and Citizen Science Sensing Networks and Platforms to Investigate the Nature and Origins of ITM System Variability

ITM system science is now mature enough to address a range of physical processes from small scale to mesoscale to large scale, but further progress is being restricted by a lack of multipoint observations of the different state variables. Significant advancement cannot be achieved with the current Explorers program, individual ground assets, and small science studies. What is now required is efficiently coordinated sensing networks and programs involving ground-based and space-based observations to understand the dynamic vertical coupling within the ITM region and other regions. The scientific community is already moving toward instrument networks and satellite constellations, matching the increased capabilities in these areas within the commercial world.

The past decade has seen the rapid growth of nontraditional space-based platforms for science observations. These platforms include CubeSats, hosted payloads, and commercial proliferated constellations. Each platform provides different capabilities that are needed to address ITM PSGs. Addressing PSG 1, 2, and 3 requires global multipoint measurements that cover a range of altitudes above 50 km. While ground-based assets provide measurements at many of the key altitudes in the mesosphere and lower thermosphere, there remain many ionosphere and thermosphere state parameters that can be observed only from space-based platforms. Ultimately, multipoint global and multiple altitude observations of ionospheric and thermospheric state variables are required to investigate the cross-scale processes within the regions and those across regional boundaries.

CubeSat subsystem technology has advanced in both capability and reliability to the point that more complex science-focused missions have become possible, as demonstrated by the significant contributions to ITM science from the NASA CubeSat missions. The NSF CubeSat program trailblazed the use of CubeSats for workforce training for both engineers and scientists. Further maturity of the CubeSat programs is needed such that resources are reflected in the required risk posture and reliability. The judicious use of CubeSats in conjunction with other space-based and ground-based observations can maximize their contribution to ITM science in the next decade.

The proliferation of commercial small satellite constellations in low Earth orbit provides a great potential resource and opportunity for system-level science for the ITM community. First, there is a growing number of commercial constellations whose business models include selling space environment observations. The best-known example is an assessment of troposphere and ionosphere GNSS radio occultation data by NOAA with the future intention of ongoing data buys. Within the next decade, the number and variety of space environment data sources is expected to grow. Second, some commercial constellations have incorporated standard open volume on individual satellites for hosted payload purchase. These hosted opportunities will enable the wide distribution of sensors that can provide different state variable observations at numerous points around the globe. Last, another potential source of space environment observations can come from "massless payloads" that leverage information from nonscience payloads or satellite subsystems to provide nontraditional observations. For example, onboard GNSS navigation receivers can potentially provide TEC and scintillation information depending on the receiver and mission downlink capability. Leveraging nonscience payloads and bus subsystems may require advanced software and processing algorithms, as well as increased downlink telemetry. This in turn will require cultivating relationships with commercial satellite constellation companies.

International partnerships and missions will play an important role in addressing ITM system science in the next decades. Budget constraints for the global ITM community necessitate that the international community work together to maximize observational capabilities. An example of a high-value potential future collaboration is joint high-latitude observations with a proposed follow-on project to the successful THEMIS–All Sky Imager (ASI) network. This network, now in implementation study, would consist of many dozens of sensors per site at more than 20 locations in Canada and provide invaluable observations that will not only enable high-latitude science studies but also enhance returns for missions such as GDC and DYNAMIC.

Citizen science efforts have demonstrated the capacity of citizen science for significant science returns, such as the identification of the subauroral STEVE phenomena in citizen-gathered photographs and widefield traveling ionospheric disturbance measurements using unique data distributions derived from amateur radio operations. Its role in ITM research, especially through increasing global multipoint observations, needs sustained encouragement through appropriately integrated activities in future projects.

Along with the increased proliferation of commercial constellations, an increase in launch vehicles and launch opportunities is expected over the next decade. These opportunities are well suited to hosted payloads, or secondary satellite missions (e.g., external evolvable launch vehicle secondary payload adapter [ESPA] class and CubeSats), to deliver ITM satellites at a variety of orbit altitudes and inclinations. Momentum is rapidly growing in these areas with attractive results. For example, SpaceX has launched hundreds of small spacecraft as rideshares, and NASA has already begun exploring this opportunity, as evidenced by CubeSats being part of the Artemis mission plan. Utilizing these various launch opportunities is essential to improve the global and altitude coverage supporting ITM system science.

The efficient utilization of the opportunities described here requires a systematic deployment and operational approach. One of the first steps needed is to determine the optimal spacing for each observed ITM state variable that is required to address PSGs 1 and 2. Thus, developing comprehensive observing system simulation experiments (OSSEs) also needs to become a priority, to ensure that an appropriate balance is achieved between utilization of the various emerging observational avenues and available funding to maximize science studies which directly address PSG topics.

D.5.2 Emerging Opportunity 2: Leverage Transformative Advances in Computer Engineering, Computational Physics, and Advanced Data Science to Understand Nonlinear, Time-Delayed, and Long-Range Causal Links Within the ITM System and Across Its Boundaries

There has been continued global investment in and ad hoc proliferation of heterogeneous, distributed networks for sensing ITM parameters in the past decade. In a number of areas, ITM science has used these tools by leveraging informal data sets of opportunity using a few monolithic instrument sites and multiple smaller networks that are sometimes anchored by a primary facility. While this architecture has made the ITM discipline the most data-rich subdiscipline of solar and space physics, ITM data are sparse in terms of data parameter types, the associated spatial coverage, and temporal continuity, which limits the communities' ability to address the PSGs of the coming decade.

The current research strategy uses a number of grant programs to encourage community exploration of data science techniques and to optimize the usefulness of current data sets. Efforts include NSF's cyberinfrastructure programs, the NASA Frontier Development Lab, NASA LWS Tools and Methods, and exploratory cross-disciplinary and interagency solicitations such as Space Weather Research-to-Operations-to-Research. NOAA's Artificial Intelligence Strategy (NOAA 2020) and its Strategic Plan 2021–2025 (NOAA 2021) identify the importance of advanced computational methods. In addition, current support for designing proposed research strategies as "high risk, high reward" encourages more innovative proposals that might have been previously rejected because reviewers lacked the subject area expertise or because of the relative newness of the proposed methods.

The large ITM science data volume and quality provides a fertile ground for the exploration and exploitation of modern data science methods. Neural networks and deep learning methods have already been implemented for various science goals, and data assimilation has matured as a technique for state estimation. The system science approach embraced by this report encompasses methods that can address complexity implicitly. However, one of the challenges in the peer-review process for proposals that use a variety of data science methods is that they may be evaluated with some skepticism by reviewers who doubt the physics-based insight to be gleaned from the data-driven methods. Further development of uncertainty quantification methods associated with artificial intelligence and machine learning algorithms are required to overcome the peer review difficulty by allowing fellow scientists to evaluate the quality of the proposed research method in answering the science questions posed. In the case of data assimilation, uncertainty quantification methods are more established, but further development of fundamental techniques for performing data assimilation is needed. The complexity of the system science focused investigations also motivates moving community work beyond single, principal investigator (PI)-led investigations toward cross-community collaborations. In all cases, it will be necessary to set quantifiable metrics to track improvements in data-driven state estimations (such as hindcasts, nowcasts, or forecasts) that will help spur progress.

For example, there is a scientific need to link small-scale kinetic effects with global (synoptic) scales that couple to produce an emergent system response comparable to that associated with a single large event. Models of global ITM dynamics can capture this type of critical cross-scale coupling only if mesoscales are resolved.

Further development of current modeling capability is needed, as accurate mesoscale modeling is a formidable task. In particular, numerical simulation of geomagnetic storms demands simultaneous incorporation of both kinetic and MHD physics over very large spatial scale ranges, along with heterogeneous conjunction data sets for driving and validation.

Owing to their complexity, geospace systems have to date been typically studied piecemeal, generally being confined to either kinetic (micro) or synoptic (large) scales, and are limited both by computing power and the sparseness (spatial, temporal, and spectral) of measurements. Implementing mesoscale capabilities will require expansive investment in modeling efforts, including the application of high-resolution computational physics and data science, as well as the combination of expertise from disciplines outside heliophysics. The result will be valuable insights from comprehensive models that simultaneously encompass global, mesoscale, and kinetic spatial and temporal scales.

ITM science can also advance through the incorporation of emerging and increasingly sophisticated machine learning applications in a number of modeling, data, and remote sensing areas. Several community input papers cited a wide variety of relevant and effective technique application categories, including modeling and theory, data tools, optimized spacecraft architectures for improved remote sensing, and space weather prediction algorithms. Thirteen ITM community input papers use the term "machine learning" and promote its use.

New computational physics, data science, and computer engineering tools provide game-changing techniques for unlocking these potentials in ITM modeling studies. The large and rapidly expanding palette of emerging capability advances for ITM studies includes computing hardware and integration advances. For example, the acceleration of graphics processing unit (GPU) computing facilitates multiscale simulations through incorporation into exascale supercomputing. Emerging capabilities also encompass computing network architectures that enable autonomous decentralized organization, unified libraries, analysis-ready cloud-optimized data sets, heterogeneous conjunction databases, and combined data products. In addition to data accessibility, access to cloud computing, open-source software (e.g., git, Python, R, julia, jupyter), and community-developed vetted analysis libraries are increasing the ability to support science findings. These advances in computing and data accessibility will also promote the development and use of explainable machine learning and pave the way for statistically based deep learning methods to be adapted for ITM science growth and discovery. Cross-disciplinary efforts will be needed to create three-way collaborations among domain science experts, mathematicians/statisticians, and software engineers.

This emerging computation-focused opportunity will enable two-way coupling of models—between scales and between regions—needed to make progress on the ITM science goals in the next decade. Exascale computing will enable the first generation of cross-scale holistic geospace models. Driven by data products from heterogeneous aggregation tools, geospace state estimation will accelerate the development of multiscale resolution physics-based simulations that are data-driven and assimilative.

D.6 IMPLEMENTATION STRATEGY

This section describes a comprehensive, balanced, and coordinated research strategy to address the ITM PSGs outlined in previous sections. This strategy is presented in terms of the following categories: large spaceflight mission concepts; ground-based facilities; other observational platforms, including Explorers and suborbital deployments; theory and modeling; and enabling capabilities.

D.6.1 Summary of Current Capabilities

Investigating the diverse physics and interrelated phenomena of the ionosphere, thermosphere, and mesosphere regions has always required a variety of observational and analysis capabilities. Over the past decade, the NSF, NOAA, and NASA portfolios have maintained the traditional combination of a few large-scale ground facilities and space missions, along with more numerous, lower-cost, focused experimental platforms, such as Fabry-Pérot interferometers, all-sky imagers, ionosondes, suborbital launches, and CubeSats, which provide observational "snapshots" of ITM state parameters in terms of either location or time. In addition to these vital measurements, more recent scientific progress has relied on model simulations and the development of state-of-the-art data science tools. New programs established in the past decade, such as NASA's Space Weather Centers of Excellence and DRIVE Science Centers, are a first step in engaging larger portions of the community in ambitious breakthrough science through the integration of available data, models, and analysis tools.

Ground-based observations have always played a key role in ITM studies, and current larger-scale ITM facility programs remain important for implementing each of the coming decade's science goals. Such programs include multi-instrument IS radar facilities, which provide comprehensive measurements of multiple state parameters at fixed locations. In the past decade, NSF decommissioned both the Arecibo Observatory and the Sondrestrom Research Facility, which ended their unique long-term observations of ITM state variability. As a result, continued operation of the remaining three NSF IS radar facilities—comprising Jicamarca Radio Observatory, Millstone Hill Geospace Facility, and the AMISR systems—is critically important for addressing PSG 4 and for improving modeling tools.

Another vital ground-based initiative is NSF's DASI program, which provides greater spatial coverage but measures relatively fewer state parameters than IS radar facilities. However, the lack of coordination among DASI components and the uncertain continuation of established platforms limits the usefulness of the data for addressing all four PSGs. In addition to DASI, grassroots and international instrument arrays have become an integral component of ITM science. Ground-based GNSS receiver arrays, magnetometer arrays, and international arrays such as the Canadian ASI network have provided valuable contextual information of state variables as well as support for phenomenological studies.

Space-based observations also remain an important part of ITM science investigations. NASA's STP and Explorer programs have contributed several important missions over the past decade. For example, the ICON mission provided the first wide-scale observational quantification of the significance of atmosphere–ionosphere coupling mechanisms and revealed the importance of winds at 100–150 km altitudes in driving ionospheric variability. The AIM mission, which was launched in 2007 to investigate noctilucent clouds, greatly exceeded its nominal 2-year mission lifetime and has provided unique and valuable constraints on the long-term variability of the mesosphere. Similarly, both the Solar EUV Experiment (SEE) and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instruments onboard NASA's TIMED satellite have operated for more than 2 decades, well beyond their planned lifetimes, and both continue to yield vital measurements of the solar ionizing flux and the state of the lower thermosphere and mesosphere, respectively.

In addition to traditional satellites, the past decade has seen a rapid expansion of diverse space-based platforms, including CubeSats, small satellites, and hosted payloads. For example, NASA's GOLD mission, which was deployed into a geostationary orbit in 2018 as a hosted payload on a commercial communications satellite, has provided high-cadence global images of Earth's thermosphere and ionosphere. These images have enabled the detection of abrupt changes in large-scale ITM structures, such as plasma bubbles. However, as noted by the 2013 decadal survey, global dynamics cannot be captured fully by a single satellite regardless of the number of instrument probes. Over a sufficiently long period of time, data from a single satellite provides a useful climatology as a function of latitude and longitude. However, such data do not provide adequate constraints on the physical coupling manifested in the continuously adjusting density, velocity, and electric current patterns (dynamics) that respond at all local times to the interconnected processes defining the ITM system and its interaction with the geospace system as a whole. As a result, historical single platform missions are ultimately limited in their usefulness to advance ITM system science.

A wide variety of models are now utilized by ITM researchers, ranging from empirical models with limited domains (e.g., IRI, DTM) to physics-based models that cover the ionosphere and thermosphere (Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics Model [CTIPe], TIE-GCM, SAMI-3) and extend from the surface to the thermosphere (WACCM-X, Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics [WAM-IPE]). Many of these models are being actively developed and improved, informed by new observations. Several of the physics-based models have been incorporated into data assimilation systems, leveraging theory and software used for weather prediction. As computing resources have grown, so has the interest in increasing model resolution and model complexity, although unresolved processes are still needed to be parameterized. Many of these models are freely available to the community, and significant progress has been made to catalog and promote access to the numerous community models maintained at NASA's Community Coordinated Modeling Center (CCMC). Efforts to couple individual models and expand their spatial domain are ongoing. The WAM-IPE model extends from the troposphere to the plasmasphere and has been incorporated into NOAA's Space Weather Prediction Center to provide thermosphere and ionosphere density forecasts. However, these efforts are not all-encompassing, and there remains a need for extensive development to improve the accuracy of models and their ability to address cross-scale coupling.

In general, the data science field has blossomed over the past decade as the generation of large data sets became accessible. Advanced tools and techniques have been applied to many geophysical areas with great success and are needed if progress is to be made on ITM system science. The region has some challenges, such as relatively sparse data coverage, disparate data sets, and lack of overall current and historical data access that currently inhibits the application of data science techniques.

NASA's DRIVE Science Center initiative, which was implemented over the past decade, has been highly successful in promoting coordinated, multidisciplinary heliophysics investigations that leverage existing observations, models, and data science tools. Among the first Phase 1 cohort of DRIVE Centers, two were explicitly focused on Earth's ITM system (CUSIA: Community for the Unified Study of Interhemispheric Asymmetries and WAVE: Wave-induced Atmospheric Variability Enterprise), while a third (MACH: Magnetic fields, Atmospheres, and Connection to Habitability) addressed ITM science on other planets.

Despite their many successes, the portfolios of the past decade are insufficient in their present form to address the coming decade's ITM priority goals focused on system science. The next decade requires a more coherent observational approach that transitions from a patchwork of individual instruments to a planned, coordinated, and sustainably supported network—both in space and on the ground—which includes more numerous but smaller multi-instrument facilities. Furthermore, the implementation of multisatellite missions with integrated ground support, such as the planned GDC and DYNAMIC missions, is required to address global-scale, comprehensive system science internal to the ITM system as well as the larger geospace environment. Additional effort is also required on comprehensive multiscale modeling, which can work closely with the system science emerging from expanded observational capabilities.

Overall, the essential component of the next decade's implementation strategy is *coordination*. The ITM community will be able to address this decade's four priority system science goals only through a paradigm shift enabled through active and frequent coordination among agencies, facilities, and programs.

D.6.2 Spaceflight Missions

To advance the ITM PSGs defined in Section D.3, the panel identified five spaceflight mission concepts that each provide critical measurements of key state parameters needed to understand the ITM as a holistic system. These mission concepts, described in the following five subsections, are notional rather than prescriptive, and their implementation would require significant additional concept development to determine optimal sensor specifications and spatiotemporal sampling modalities needed to address the science goals of the mission. Moreover, the five mission concepts reflect the diversity of ITM studies needed to address the complexity of ITM physics, which is incompatible with the concept of any single all-encompassing mission concept.

BRAVO

Implementation strategy: Implement a multiplatform mission that integrates a heterogeneous satellite constellation and ground-based observations to vertically trace gravity wave energy and momentum flux from the lower atmosphere through the ITM and to determine impacts of these processes on mesoscale dynamics.

The lack of observations on the vertical evolution of gravity wave influences is a key impediment to our understanding of how and to what extent low-altitude forcing influences the ITM. At present, gravity waves can be observed only in discrete altitude ranges in the mesosphere and thermosphere with individual ground- and space-based sensors that have significant horizontal separation. These relative point observations have proven insufficient to discern the influence of the waves on the thermospheric horizontal wind field and ionospheric density structures.

In the absence of quality measurements, researchers resort to models and less direct observational techniques to attempt to connect potential gravity wave effects. These studies of gravity wave generation, propagation, and breaking must apply assumptions to fill in missing observational gaps for momentum and energy transport, and these assumptions impact the ability to assess these forcing influences on ITM structure. Thus, the community needs detailed experimental knowledge of the vertical evolution and structure of gravity waves from their generation in the lower atmosphere through the mesopause and upper atmosphere.

The Buoyancy Restoring-force Atmospheric-wave Vertical-propagation Observatory (BRAVO) mission concept is a Solar Terrestrial Probes (STP)-class effort designed to address these gaps and provide the quality data that is needed to understand the influence of gravity waves on the ITM system. The BRAVO science goal is to explain the ITM effects of momentum and energy transport and deposition through direct uninterrupted observations of their propagation from the lower atmosphere to their breaking in the ITM. The specific science objectives are to

1. Quantify the spatiotemporal dependence of lower-atmosphere gravity wave momentum/energy flux incident upon the thermosphere and ionosphere.
2. Determine the evolution of gravity wave influences on the lower and middle thermosphere.
3. Connect gravity wave influences in the lower/middle thermosphere to ionospheric impacts.

BRAVO will provide the first continuous vertical observation of gravity wave propagation and dissipation throughout the mesosphere–thermosphere system and determine the subsequent effects of these processes on the thermosphere and ionosphere. This will be achieved by employing a combination of cutting-edge orbiting sounders and airglow imagers along with large networks of ground-based GNSS receivers, and meteor radars. The required measurements include gravity wave parameters, neutral winds, neutral temperature, O and O^+ composition, and plasma density between 90 and 400 km. Table D-2 details the required measurements for BRAVO and the detailed observables required to address the BRAVO science objectives.

TABLE D-2 Science Traceability for the Buoyancy Restoring-force Atmospheric-wave Vertical-propagation Observatory (BRAVO) Mission Concept

Science Objectives	Measurement Objectives	Required Observables
1. Quantify the spatiotemporal dependence of lower-atmosphere gravity wave momentum/energy flux incident upon the ionosphere–thermosphere system.	Determine the horizontal gravity wave field in the mesopause region (85–90 km). Determine the vertical gravity wave structure in the mesopause region. Determine the global-scale mesosphere–lower thermosphere bulk flow neutral winds.	Gravity wave parameters near mesopause (~90 km): • Neutral wind • Temperature Global large-scale gravity waves and the background state (90–400 km at 500 km horizontal resolution): • Horizontal neutral winds • Neutral temperature density • F-region peak density and altitude
2. Determine the evolution of gravity wave influences on the lower/middle thermosphere.	Determine the height-resolved mean state of the neutral temperature. Determine the lower thermospheric neutral winds relationship with lower altitude gravity waves. Ascertain gravity wave effects on the mean state of mesosphere/thermosphere neutral density. Determine physical interactions between tidal motions and gravity waves.	Small-scale gravity wave field for regional studies (80–100 km at 30 km spatial resolution) TEC (at 30 km spatial resolution and delta TEC <1%)
3. Connect gravity wave influences in the lower/middle thermosphere to ionospheric impacts.	Identify and quantify mesoscale and small-scale plasma density structuring. Determine the processes that drive horizontal and vertical effects on the ionosphere mean state owing to thermospheric density structures such as traveling atmospheric disturbance. Ascertain the extent of coupling between ionospheric density structures and mean state perturbations.	[O^+], [e-] altitude profiles (≤1 scale height resolution) S4 scintillation index

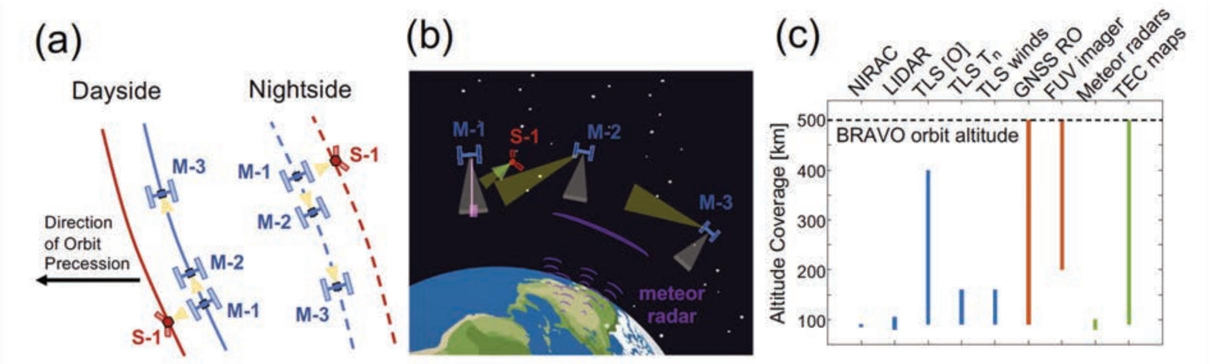


FIGURE D-19 (a) Distribution of primarily nadir looking instruments (blue) and the outrigger platform (red), along with their limb-scanning fields of view (yellow). (b) The various sensors' field-of-view distributed among the Buoyancy Restoring-force Atmospheric-wave Vertical-propagation Observatory (BRAVO) constellation. (c) The vertical coverage of the neutral and plasma observations (in red and blue, respectively), along with the vertical coverage of supporting ground-based instrumentation (in green).

Mission Configuration, Deployment, and Operations

The nominal BRAVO mission configuration reflects the key science requirement for common volume observation of a vertical atmospheric column along multiple perpendicular directions to determine altitude-resolved horizontal wave fields and propagation. BRAVO achieves this common volume sensing using a constellation of four satellites in circular orbits at 500 km altitude and 50-degree inclination. The satellites are asymmetrically distributed in two orbital planes with their nodes separated by 20 degrees to achieve common volume sensing with proper coverage. Three satellites denoted (M1, M2, and M3) are in one plane and satellite S1 is in a separate plane with slewing as needed to maintain sensor viewing orientation toward M1. Within the first orbit plane, M1 and M2 are separated by ~4 minutes to focus on small spatial and temporal waves that dominate the mesosphere and lower thermosphere wave field. Satellites M2 and M3 are separated by ~20 minutes to capture the larger waves in the middle thermosphere. This configuration will precess at a rate of ~4 degrees per day, resulting in full longitude coverage in 90 days (day and night) providing observations of seasonal and longitude sector variability.

The combination of BRAVO on-orbit observations and ground-sensor arrays will provide vertical altitude coverage of plasma and neutral densities throughout the ITM, as illustrated in Figure D-19. To observe complete information on gravity wave vertical propagation, the BRAVO mission concept features the following sensors:

- A nadir-oriented sodium LiDAR on satellite M1, which measures neutral temperature and winds along the vertical line of sight from 80–105 km.
- Near-infrared airglow cameras (NIRACs) on satellites M1, M2, and M3, which measure the horizontal neutral wind field via imaging of OH emission near 85 km.
- Terahertz limb sounders (TLSs) on satellites M2, M3, and S1, which measure neutral oxygen density [O] from 90–400 km and neutral temperature T_n and line-of-sight winds from 90–160 km via limb scanning.
- A far ultraviolet (FUV) 135.6 nm imager on satellite S1, which measures O^+ density from 200–500 km.
- GNSS radio occultation (RO) sensors on satellites M1, M2, M3, and S1, which measure electron density from 90–400 km.
- A network of ground-based meteor radars, which measure the neutral wind at high resolution from ~80 to ~100 km altitude from observations of sporadic meteor trail scatter.
- A network of ground-based GPS receivers, which provide maps of ionospheric TEC.

The nominal launch strategy is for all four satellites to be on a single launch followed by a separation into two orbital planes. All four satellites will be 3-axis stabilized with a 0.076-degree pointing requirement for the M1 satellite hosting the Na LiDAR, which is considered to be the anchor instrument. The other satellites are arranged so that the field of view of their sensors will provide observations of the same vertical volume either coincident with or shortly behind M1. The S1 satellite will perform a slew maneuver twice per orbit to maintain a coincident field of view of its limb sounder with the M1 sensors. This distribution of the BRAVO satellites and sensors is designed to provide both vertical and horizontal observations of the gravity wave field.

Because the BRAVO sensors provide only a local "snapshot" of the vertical and horizontal gravity wave field, it is imperative to have the support of a network of meteor radars and GNSS sensors observing simultaneously within the BRAVO sensed volume. This will enable tracing of the horizontal wind fields and assessment of their global and mesoscale effects on the ionosphere.

Baseline Mission and Possible Descopes

The notional BRAVO baseline mission, including both the space- and ground-based components, is specifically designed to achieve its science objectives. One of the primary challenges for BRAVO is the trade-off between on-orbit data storage and the scheduling of frequent ground station contact time for the downlink of the high volume of science data associated with the infrared airglow imager and LiDAR instruments. The terahertz limb sounder instrument requires design maturation and qualification testing to raise its technology readiness level (TRL) from TRL 4 to TRL 6. Additionally, the nadir-oriented sodium LiDAR instrument needs to be matured from TRL 5 to TRL 6. While there are no descope options that would allow for meaningful closure on the mission science objectives, several enhancements to the mission's ground and space segments will provide significant science and operational improvements. For example, the inclusion of a second outrigger satellite, identical to S1 but orbiting in the plane opposite to M1, would remove the need for slewing maneuvers, resolve spatiotemporal aliasing and ambiguities, and increase horizontal coverage to provide a three-point map of the neutral wind structure variability. Additional ground sensors, such as all-sky imagers, LiDARs, and digisondes, would provide more comprehensive direct observations of gravity wave/ionosphere coupling by increasing the bottomside ionospheric structure resolution.

Expected Outcomes

The BRAVO mission is designed to provide critical insights into the physics of momentum and energy exchange that results from gravity wave propagation and the associated thermospheric wind field and ionospheric structures, thus directly addressing PSGs 1.1, 1.3, and 1.4. The innovative combination of high-resolution space-based observations with large meteor radar network observations of the horizontal wind field will transform our understanding of internal processes and dynamics of the important mesopause region and its coupled influence on the ITM (PSGs 2.1 and 2.3). Furthermore, BRAVO's cutting-edge sensors and ground networks will provide direct and quantifiable measurements of the neutral wind field and its influence on ionospheric structures at key spatial scales (PSGs 3.1 and 3.2).

Resolve

Implementation strategy: Deploy a dense constellation of space-borne sensors monitoring the neutral wind, temperature, and density in the lower thermosphere, in order to resolve the pathways for global-scale energy and momentum transport from the lower atmosphere to the middle and upper atmosphere.

Missions of the past 2 decades have revealed that global-scale waves (e.g., tides and planetary waves) are a critical pathway for momentum and energy transport from the lower atmosphere to the ITM. Both their coupling and nonlinear feedback are thought to contribute substantially to short-term weather of the ITM. However, such processes are generally not observable by previous or planned missions, which monitor only a small number of locations at a time (often just one). A large constellation mission would enable the first continuous global picture of weather at the boundary of geospace.

As an LWS mission, the Resolve science goal is to determine the pathways for energy and momentum transport from the lower atmosphere to the middle and upper atmosphere. The science objectives are to

1. Determine the processes by which mean flow, tides, and planetary wave evolution and propagation are modified by external energy and forcing.
2. Establish to what extent lower atmospheric forcing can explain the observed ionospheric variability on similar timescales.
3. Determine the mechanisms underlying the detailed nonlinear interactions between mean flow, tides, and planetary waves that combine to produce the observed variations.

The notional Resolve implementation leverages advances in sensor miniaturization and low-cost access to LEO. It consists of a constellation of several dozen CubeSats, each carrying a single sensor that remotely senses vertical profiles of thermospheric parameters, in several different orbit planes, and observes the daily weather of global mean winds, tides, planetary waves, and large-scale gravity waves. The required measurements include the horizontal neutral wind and temperature in the lower/middle thermosphere and the atomic oxygen density throughout the thermosphere. See Table D-3 for details.

These measurements will allow for transformative progress on PSGs 1–3. Specifically, the immediate, global effect of lower atmospheric events (e.g., SSWs, ENSO, volcanic eruptions) on the global wave spectrum will be observed for the first time (PSG 1.1). The short-term effects of lower atmosphere forcing on the mean state and variability will be directly monitored (PSG 1.3), and the measurements will enable mechanism studies of the transition of chemical, dynamical, and thermal energy regulated by waves in the critical ~100–200 km region (PSG 1.4). Resolve will enable the first comprehensive studies of tidal/planetary wave interactions and their impacts on the ionosphere, wave/mean-flow interactions, and some aspects of tidal/gravity wave coupling (PSG 2.3). The mission will also quantify the efficiency of lower atmosphere forcing of day-to-day variability and quantify the dominant waves driving mesosphere/thermosphere weather (PSG 3.2).

TABLE D-3 Science Traceability for the Resolve Mission

Science Objectives	Measurement Objectives	Required Observables
1. Determine the processes by which mean flow, tides, and planetary wave evolution and propagation are modified by external energy and forcing.	Determine how the lower atmospheric forcing of the upper atmosphere, on horizontal scales greater than ~3,000 km, varies on day and hour timescales. Ascertain under what conditions lower atmosphere forcing dominates the upper atmospheric dynamics and energy budget. Determine the impact of magnetospheric and solar energy input on the thermospheric wave field.	Horizontal neutral wind (90–160 km altitude at 1 km resolution) Neutral temperature (90–160 km altitude at 5 km resolution) Atomic oxygen density (90–400 km altitude at 5 km resolution) Revisit latency <20 min for gravity wave; instrument sampling rate >0.02 Hz
2. Establish to what extent lower atmospheric forcing can explain the observed ionospheric variability on similar timescales.	Quantify the timescales of the gravity wave field produced by lower atmospheric events. Quantify the daily global tidal wind field.	
3. Determine the mechanisms underlying the detailed nonlinear interactions between mean flow, tides, and planetary waves that combine to produce the observed variations.	Determine the horizontal global wave field and its evolution in time with near-instantaneous observations. Determine the vertical global wave field and its evolution in time with near-instantaneous observations.	

Mission Configuration, Deployment, and Operations

The requirement for daily characterization of all global-scale waves necessitates the implementation of a global constellation. Modeling studies have suggested that features up to zonal wavenumber 12 could carry significant energy contributing to global structures like the Midnight Temperature Maximum. This drives a requirement for near simultaneous measurements at 24 local times.

The nominal Resolve mission configuration, shown in Figure D-20, thus comprises 72 identical spacecraft populating 12 circular orbit planes at a uniform altitude between 500 and 700 km. The spacecraft in each plane are equally spaced (60 degrees along-track spacing with a revisit time of ~15 minutes). Each spacecraft can be operated to observe either along-track, to sample the meridional wind, or cross-track for zonal wind characterization. Interleaving along-track and cross-track viewing spacecraft in the same orbit plane (i.e., three each per plane) minimizes the need for interpolation of line-of-sight observations to estimate vector winds. A comprehensive OSSE would be useful for further optimization of the distribution of orbital planes, spacecraft, and the look directions within each plane.

The notional spacecraft is a 3-axis-stabilized 6U CubeSat bus with a single instrument to observe vertical profiles of line-of-sight neutral wind, temperature, and atomic oxygen density, at all latitudes, longitudes, and local times.

The nominal strategy is to deploy 12 CubeSats on each of six separate launches. After separating the orbits to achieve global coverage, the operational strategy does not change. For the 6 spacecraft in each plane, the preference is to maintain an approximately equal 60-degree separation. There is no requirement to synchronize spacecraft on different planes. Occasional on-orbit failures do not significantly detract from science capability owing to the redundancy inherent in a constellation mission. The design life for each spacecraft is approximately 3 years.

Baseline Mission and Possible Descopes

The Resolve baseline mission described here is designed to achieve the science objectives. The primary challenge for Resolve is the timely manufacture, launch, and deployment of the 72 spacecraft constellation within the design lifetime of the spacecraft. The production capacity for the 72 instruments and spacecraft buses can be met by contracting with multiple vendors for both the instruments and spacecraft buses for parallel manufacturing.

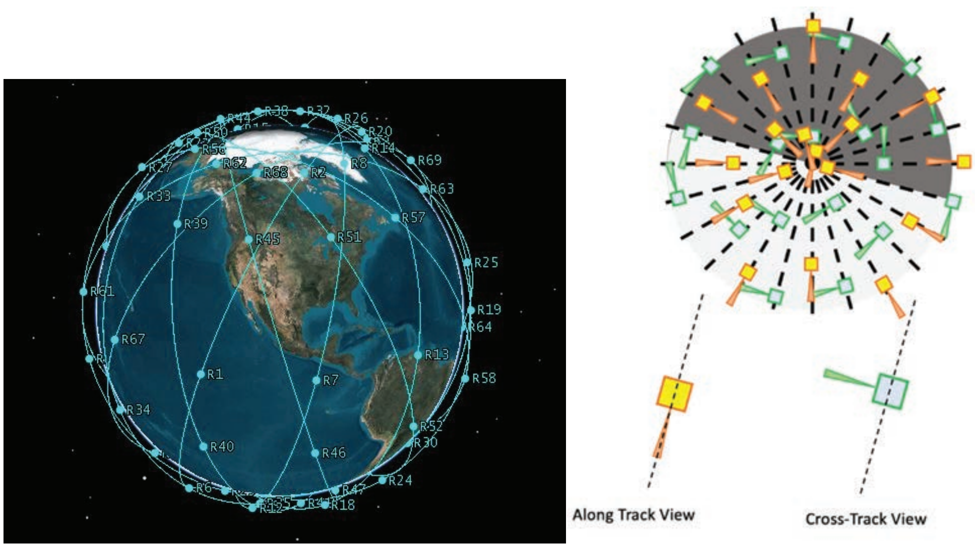


FIGURE D-20 (*Left*) Snapshot of Resolve constellation orbital configuration. (*Right*) Distribution of cross-track (blue) and along-track (yellow) CubeSats.

Additionally, multiple launch vehicle vendors may be needed to deploy the spacecraft in large batches. Descope options to accommodate the manufacturing challenge include reducing the number of spacecraft or spacing launches in time. Such changes would impact spatiotemporal resolution, particularly at mesoscales, and OSSE modeling would be needed to evaluate optimal configurations to target specific wave modes.

Expected Outcomes

Resolve would revolutionize the understanding of how global-scale atmospheric waves propagate, interact, and impact the ITM. This mission concept builds on the understanding gained from previous single-spacecraft missions such as TIMED, ICON, and GOLD by providing a global view of the 100–200 km altitude region for the first time. The mission is also highly complementary to GDC, which observes the ITM in situ. It will also augment DYNAMIC's ability to address cross-scale coupling (PSG 2) and short-term boundary forcing (PSG 1) if the DYNAMIC implementation is limited to two spacecraft. Strong synergy also exists with ground-based instruments capable of Earth-fixed observations of winds and waves, including but not limited to IS radars, LiDARs, Fabry Pérot interferometers, and meteor radars. In addition to the scientific impacts, Resolve is well suited to advancing the space-weather monitoring capability by comprehensively specifying the spatiotemporal dependence of lower atmospheric drivers and their effect on thermospheric density and satellite drag. Resolve's multipoint sampling method is an ideal candidate for data assimilation in operational models, which are currently data-starved in the thermosphere.

Interhemispheric-Circuit

Priority implementation strategy: Deploy a heterogeneous satellite constellation combining continuous imaging of both auroral ovals from space with simultaneous, spatially distributed, lower ionospheric in situ observations to quantify the coupling between interhemispheric ITM asymmetries, auroral currents, and precipitation energy deposition.

Interhemispheric asymmetries in the ITM are both a result of and a driver of a complex network of competing electromagnetic plasma processes, regulated by differences in the distribution of hemispheric open flux, energetic particle precipitation, and the energy flow that transforms the global magnetosphere–ionosphere–thermosphere electric current system. Understanding these asymmetries and their drivers is essential for resolving core PSG questions on ITM boundary transport, cross-scale coupling, system scale variability, and determination of relative process importance.

The Interhemispheric-Circuit (I-Circuit) notional mission is an implementation in the STP line that will provide crucial information for the understanding of how the exchange of energy and momentum regulates and is regulated by the global system of horizontal and interhemispheric currents that connect the magnetosphere with the conjugate ionospheres. This will be accomplished with coordinated heterogeneous streams of auroral images and simultaneous in situ ionospheric data from magnetically conjugate latitudes that will provide critical insights into the global-scale electromagnetic current system and enable the validation and refinement of physics-based models.

The specific science objectives are

1. Determine which parameters of the magnetosphere–ionosphere–thermosphere–mesosphere system regulate Earth's global current circuit.
2. Understand the nature and origins of hemispheric asymmetry.
3. Understand the impact of interhemispheric asymmetry on the global ionosphere–thermosphere system.

I-Circuit constitutes a major advance for solar and space physics science by addressing the causal relationships between fundamental physical processes that are distributed in space, in scale, and in parameter space. A new level of understanding of geospace will be achieved through the simultaneous global measurements of interconnected state variables. I-Circuit offers (1) breakthroughs in understanding interhemispheric asymmetries of currents, ion drifts (electric fields), particle precipitation, conductivity, neutral densities, and winds that result from the interaction between the atmosphere, ionosphere, and magnetosphere; (2) fundamental discoveries of global ion-neutral

TABLE D-4 Science Traceability for the Interhemispheric-Circuit (I-Circuit) Mission

Science Objectives	Measurement Objectives	Required Observables
1. Determine which parameters of the magnetosphere–ionosphere–thermosphere–mesosphere system regulate Earth's global current circuit.	Determine the relationship between large-scale and mesoscale currents and relate solar wind and geospace conditions to measurements of all three components of the current connecting the magnetosphere–ionosphere system.	• Horizontal neutral wind and temperature (90–160 km altitude). • Density profiles of H, O, O_2, N_2, NO, and O^+. • Column densities of O, N_2, and NO. • Energetic electron spectra 10 eV to 30 keV, and 30 keV to 1 MeV key parameters. • Ionospheric electric fields and plasma flows. • Field-aligned currents. • Thermospheric emissions for OI 135.6 nm, N_2 Lyman-Birge-Hopfield (LBH) short (140–150 nm), N_2 LBH long (165–180 nm), and H 121.8 nm for the whole auroral oval and the polar cap, including global and regional auroral boundaries.
2. Understand the nature and origins of hemispheric asymmetry.	Determine the asymmetry of the global current circuit, the hemispheric open flux, and the precipitation of energetic particles to quantify auroral conjugacy using simultaneous observations in both hemispheres.	
3. Understand the impact of interhemispheric asymmetry on the global ionosphere–thermosphere system.	Determine the spatial and temporal variation of the ionosphere and the thermosphere, and couple the electrodynamics of imaged mesoscale processes to large-scale electrodynamics through longitudinally separated observations.	

coupling and feedback processes active in the geospace-atmosphere system; (3) unprecedented knowledge about how the ionosphere–thermosphere system responds to variations in solar EUV irradiance, tropospheric forcing, and solar wind; and (4) the interhemispheric data suitable for validating and advancing space weather models.

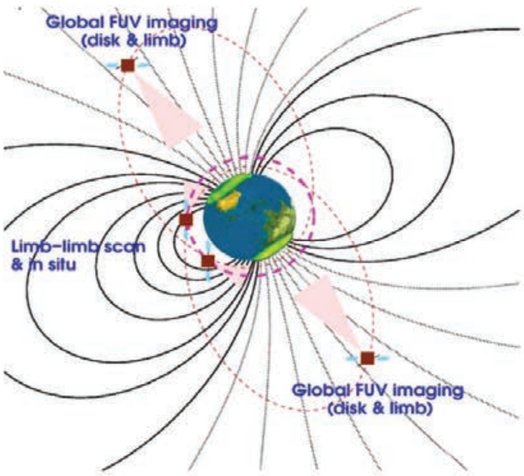
Table D-4 details the required measurements for I-Circuit and the detailed observables required to address the I-Circuit science objectives. (Note as well that the required observables allow key derived quantities such as ionospheric conductivity to be calculated.)

Previous community attempts in the past decades to address I-Circuit mission science areas have provided limited temporal, spatial, and parameter coverage for subelements of interhemispheric processes, but lacked auroral imagery to provide important context. In particular, none of the previous missions has provided a heterogeneous array of common volume observations on a deliberate rather than ad hoc conjunction basis. The I-Circuit mission design closes these gaps by employing two HEO auroral imaging satellites that give a global view of key state parameters while multiple LEO satellites provide simultaneous in situ information of conjugate ionospheres. With this configuration, as depicted in Figure D-21, I-Circuit delivers the necessary global simultaneous observations covering all latitudes and local times that will enable significant advances toward PSG 3.4.

The I-Circuit measurement objectives address the preceding science objectives as follows:

- Science Objective 1 requires the determination of the relationship between large-scale and mesoscale currents and relates solar wind and geospace conditions to measurements of all three components of the current connecting the magnetosphere–ionosphere system.
- Science Objective 2 requires the determination of the asymmetry of the global current circuit, hemispheric open flux, and the precipitation of energetic particles to quantify auroral conjugacy using simultaneous observations in both hemispheres.
- Science Objective 3 requires the determination of the spatial and temporal variation of the ionosphere and the thermosphere and the electrodynamics of imaged mesoscale processes to large-scale electrodynamics through longitudinally separated observations.

In addition to the requirements on the state parameters themselves (see Table D-4), there are requirements on combinations of the observables. Simultaneous parameter quantification is needed between hemispheres locally, regionally, and across hemispheres down to auroral arc scales. This requires a distribution of observation points to allow interhemispheric, regional, and auroral arc-scale observations with specific resolutions, cadences, and separations. Assimilative physics-based modeling tools are needed to aggregate and interpret the observations.



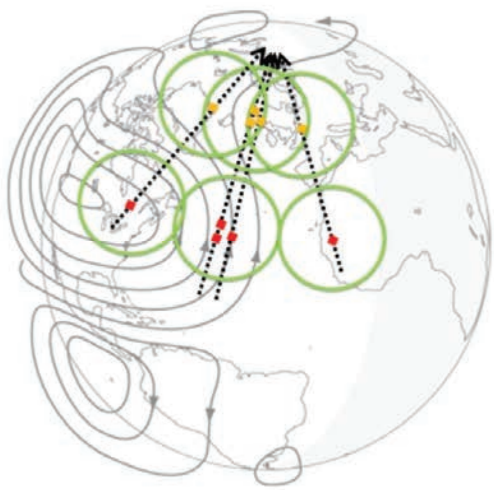


FIGURE D-21 The I-Circuit satellite constellation. The left image illustrates the 2-spacecraft HEO aspect of the constellation. The right image illustrates the 10-spacecraft LEO aspect.
SOURCES: (*Left*) Liou et al. (2022), https://baas.aas.org/pub/2023n3i241/release/1. CC BY 4.0; (*Right*) Yee et al. (2022), https://baas.aas.org/pub/2023n3i439/release/1. CC BY 4.0.

Mission Configuration, Deployment, and Operations

I-Circuit addresses the measurement objectives using global, common volume sensing by heterogeneous platforms in both high (HEO) and low Earth orbit (LEO). The two identical HEO satellites are in highly elliptical (600 km × 12 Re), high inclination (~116°), Molniya-like orbits, with their arguments of perigee spaced 180° apart. They provide auroral FUV imagery and measurements of electron precipitation distributions simultaneously in conjugate hemispheres. At the same time, a suite of 10 identical LEO satellites are distributed in circular, ~600 km altitude orbits across four intersecting planes. They gather simultaneous measurements of key ionospheric and thermospheric parameters in both polar hemispheres by virtue of their large (97°) orbital inclinations.

The LEO platforms have identical suites of instruments to measure neutral and ionized composition, winds, and fields to fully describe the key parameters of the IT system. The LEO satellites host a Global Ultraviolet Imager (GUVI+), TLS, microwave electrojet magnetogram (MEM) sensor, magnetometer (MAG), ion velocity meter (IVM), electron spectrometer (E-Spect), and electric field sensor (E-Field). The LEO orbital configuration, shown in Figure D-21, features two closely spaced orbits with 0.064-degree right ascension of the ascending node (RAAN) separation and two outrigger orbits with 40 degrees of RAAN separation. The spacing along and across the various orbital planes is designed to support curlometer calculations in each auroral oval, conjugacy observations across both ovals, and overlap of TLS and field observations between orbit planes at auroral latitudes. The orbits drift in local time but maintain their mutual spacing.

I-Circuit's 12 different satellites (10 LEO, 2 HEO) can be placed in orbit with multiple launch vehicle options. The LEO constellation can be achieved using two different launch vehicle types, one for the 6 center-plane spacecraft constellation and another for the 4 outrigger-plane spacecraft. A nominal launch scenario consists of a single heavier class vehicle for the center-plane spacecraft and two launch vehicles (two spacecraft on each) for the outrigger-plane spacecraft. The HEO constellation could be achieved with a single launch vehicle employing a multiple payload canister deployment system. Each spacecraft would require a motor for apogee boost. All spacecraft have nominal 30- to 32-month lifetimes, are 3-axis stabilized, and use onboard propulsion for orbit phasing and maintenance.

No additional instrumentation is required for I-Circuit science closure in the given concept definition. However, coordination with existing ground-based and suborbital flight assets, such as THEMIS-GBO (and its Canadian follow-ons planned in conjunction with GDC), Millstone Hill IS Radar, PFISR/RISR, EISCAT, SuperDARN, and

Poker Flat sounding rockets would be valuable and provide significant additional data constraints for I-Circuit data interpretation. For example, IS radars would provide full altitude profiles of key parameters, auroral imagers would provide multiscale information alongside the I-Circuit data, and rocket experiments would help to constrain the horizontal extent of Joule heating.

Baseline Mission and Possible Descopes

Based on current production rates, the estimated schedule for fabrication, integration, and testing of I-Circuit's numerous, well-instrumented LEO spacecraft is likely to be significantly longer than that of previous ITM missions. This production rate is driven primarily by an assumed set of NASA spacecraft reliability requirements (as opposed to commercial). However, the changing landscape of commercial spacecraft fabrication capabilities may reduce development time as well as cost. The nominal spacecraft lifetimes (LEO 30 months, HEO 32 months) are limited by overall reliability assuming single-string failures. Further studies are needed to consider the offsetting possibilities of the multiple observation points on science resiliency.

Possible descopes include lower inclination LEOs, which would hasten the orbital precession and array formation, and one fewer outrigger LEO orbit. However, both descopes have severe impacts on science return and would require careful assessment in the context of various costing assumptions.

Expected Outcomes

I-Circuit outcomes would benefit the wider heliophysics community through mission goals that focus on high-latitude effects where magnetosphere–ionosphere coupling is strong and fundamental. Ionospheric current closure is a key unknown for magnetosphere dynamics that is not fully accounted for in global models. The simultaneous images of conjugate ionospheres would provide important context for magnetosphere studies. I-Circuit is also highly synergistic with space weather research. For example, LEO is becoming a congested space for vehicles and debris. A lack of understanding of small-scale variability effects, such as regional drag variations that are associated with differential thermospheric heating, affects the ability to control on-orbit constellations. Ionospheric structure forecasting is also vitally important for end users of transionospheric RF systems.

The I-Circuit mission directly addresses

- *PSG 1.2:* Transport processes across the high-altitude/latitude ITM boundary, both through the coupling among the solar wind, magnetosphere, and ITM through field-aligned electric currents and energetic particle precipitation and the horizontal coupling through ionospheric closure currents and vertical coupling through the ionospheric conductivity volume.
- *PSG 2.2:* Cross-scale coupling at high latitudes is addressed with observations spanning local auroral arc scales, conductivity pattern scales, and global scales.
- *PSG 3.4:* Resolving competing processes and identifying causality, is addressed through observational validation of the modeling of substorm evolution, and of the two-way coupling of interhemispheric conjugacy and asymmetry.

LAITIR

Ion-neutral coupling below 200 km altitude remains a frontier ITM topic through the important process of Joule heating, which drives the geospace environment through multiscale transformation of mass, momentum, and energy with profound impacts throughout the entire ITM system. The Low Altitude Ionosphere and Thermosphere In situ Researcher (LAITIR) notional mission is a STP-class "dipper" to explore the undersampled lower thermosphere below ~200 km altitude. This mission is composed of three sequentially launched satellites with lifetimes of approximately 3 years each, yielding a total mission period of 8 years to cover most of a solar cycle. The highly elliptical, high-inclination orbit will require an aerodynamic vehicle with propulsion to perform periodic campaigns to perigee altitudes below ~150 km to make in situ measurements of ions, electrons, neutrals, winds, electric fields, and magnetic fields. In situ measurements of this region are scarce: the last such measurements were obtained for only 1 year with more than 50-year-old technology by the Atmospheric Explorer-C (AE-C) platform in 1974, a low solar activity period.

The science objectives of LAITIR are to

1. Determine how ionospheric Joule heating is influenced by and influences neutral wind, composition, temperature, and density.
2. Determine how spatial and temporal variations in density, composition, and temperature of the neutral lower thermosphere (100–200 km) and ionosphere depend on preconditioning and solar activity.
3. Determine the conditions under which non-Maxwellian processes regulate ion-neutral coupling.

LAITIR Objective 1 links to PSG 1 through investigating how Joule heating transforms mass, momentum, and energy. Joule heating is the largest and most variable energy deposition process in the ITM and drives global thermosphere circulation. Current Joule heating estimates vary by up to 500 percent. LAITIR Objective 2 links to multiple PSGs by studying how the sun drives the thermosphere and ionosphere from above (PSG 1.2), by examining the different scales of variability within the ionosphere and thermosphere (PSG 2.4), and by allowing the examination of slowly varying trends. AE-C measurements from 50 years ago were severely limited and, although the technology was impressive for that time, its limited dynamic range has impeded subsequent studies of Joule heating and other variations in this undersampled region of Earth. LAITIR overcomes the limitations of AE-C by directly and simultaneously observing the ionosphere and thermosphere electrodynamics with modern instrument capabilities over most of a solar cycle. Last, LAITIR Objective 3 links to PSG 2.2 and 3.2 by investigating how ion-neutral coupling behaves on different scales, by establishing where fluid approximations are less appropriate, and by determining the conditions under which non-Maxwellian behaviors are dominant.

Mission Configuration, Deployment, and Operations

The baseline, notional LAITIR mission would deploy three satellites sequentially into high inclination (>85 degrees) and highly elliptical orbits so that they overlap every 6 months and return data over approximately 3 years. Approximately 80 percent of the time, these aerodynamic satellites would be in a "survey" orbit with an apogee of 250 km and perigee of 1,500 km. As the perigee precesses to high latitudes in either hemisphere, each LAITIR spacecraft would perform perigee-lowering maneuvers to <150 km in a dipping campaign mode lasting approximately 15 days. When the perigee precesses out of the high-latitude region, propulsion maneuvers would raise the satellite back to the survey orbit. Approximately 15 "dipping" campaigns are expected in the 3-year lifetime of each satellite, yielding ~45 total dipping campaigns during the mission. The spacecraft instrumentation ideally includes an ion drift meter, an ion/neutral mass spectrometer/retarding potential analyzer instrument (for measuring ion density/temperature, ion composition, neutral composition/temperature, and winds), an electric fields instrument, a magnetometer, and an electron spectrometer (to measure auroral and photoelectrons).

A dipper mission is currently being studied by the EnLoTIS working group, and other similar low-perigee missions have been previously proposed multiple times by the community but not pursued due primarily to agency priorities and budget constraints. These earlier proposals include the Geospace Electrodynamics Connections Explorer (GEC), Daedalus (Sarris et al. 2020), and Atmosphere–Space Transition Region Explorer (ASTRE). Meanwhile, GEC was identified as being a high priority for implementation in the 2003 decadal survey and planned for launch in 2007, but the concept was never pursued in the configuration described. While pieces of GEC have been incorporated in the GDC and DYNAMIC mission concepts, these planned missions will not directly sample low altitudes and will not constitute a complete single platform package for ion-neutral coupling studies. Simultaneous measurements of all parameters along the orbit are crucial for science analysis without problematic assumptions in this region dominated by complex ion-neutral interactions.

A dipper mission presents significant technical challenges. The low-altitude environment requires designs tailored to a relatively high atomic oxygen density and aerothermal heating. Furthermore, trade-offs between the frequency of low-perigee campaigns and the altitude reached by each campaign will need to be studied with respect to specific science objectives, mass and propulsion margins, and detailed drag modeling.

Baseline Mission and Possible Descopes

There are several potential descope options for LAITIR. Having fewer consecutive launches would decrease mission cost but would also decrease the temporal baseline and significantly impact the ability to perform studies yielding dependence of these processes on solar cycle conditions. Using 12U CubeSats or smallsats is a potentially attractive solution but requires a trade study and further analysis to set the total minimum number of mission hours for science closure (e.g., minimum statistically significant Joule heating events, needed local time and seasonal coverage ≤150 km, required coverage >L = 3.5).

No ground-based instrumentation is required for science closure. However, potential science enhancements could be achieved using ground-based instrumentation. IS radar observations would provide full altitude profiles of ionospheric density and drifts, auroral imagers would provide multiscale information alongside the LAITIR data, and rocket experiments would help to constrain the horizontal extent of Joule heating. Synergy with other heliophysics disciplines, particularly MAG, could be achieved with the notional LAITIR mission through its electric and magnetic field measurements that characterize Region 1/Region 2 current systems and polar cap potential drop. The electron spectrometer with higher energy channels could characterize the auroral electron precipitation events as well as provide additional localizing information on magnetospheric electron populations and acceleration region boundaries. Gaining a better understanding of Joule heating and the densities of the lower thermosphere would enable significant advances in space weather forecasting, especially during geomagnetic events.

Expected Outcomes

The notional LAITIR mission described here will produce several compelling science results. These include (1) quantifying Joule heating leading to provide better modeling and forecasting of this key driver which is sorely needed in the thermosphere and ionosphere variability community (PSGs 1.2, 1.4, 2.2, 3.3); (2) establishing the background state of the high-latitude transition region of the lower thermosphere in terms of composition, temperatures, and winds (PSG 1.4); and (3) advancing understanding of the conditions under which non-Maxwellian processes regulate ion-neutral coupling, thus advancing modeling of the ITM system (PSGs 2.2, 2.4).

SOURCE+

Implementation strategy: Augment the SOURCE mission to elucidate the coupling between the ITM mass distribution and ion outflow at multiple spatial scales.

The Magnetospheric Synchronized Observations of Upflow, Redistribution, Circulation, and Energization (SOURCE) mission concept, an STP-line implementation, tracks plasma flows from the ionosphere and through the magnetosphere to understand the processes and pathways by which core magnetospheric ions flow from the ionosphere and are energized and redistributed within and throughout geospace. Understanding of these processes and pathways is crucial because core plasma dynamics and associated mass exchange are a critical component of the space environment and are fundamental for understanding the coupled ionosphere–plasmasphere–magnetosphere system and its dynamics.

With the modest addition of two satellites that are focused on ionosphere–thermosphere observations of the source and sink of magnetosphere ions, the SOURCE mission would become a more comprehensive system science mission that enhances the understanding of the resulting neutral and ionospheric processes driven by magnetospheric ion outflow as well the processes underlying the spatial and temporal variability of ionospheric outflow to the magnetosphere.

The augmented mission, designated SOURCE+, will add two science goals to the four original SOURCE mission science goals defined in the MAG report (see Appendix C). These new goals focus on understanding the relationship between the outflow aspect of the cold plasma lifecycle and ionosphere–thermosphere dynamics. The SOURCE+ objectives are

1. Determine the physical processes of horizontal neutral mass flow that regulate ion upwelling and outflow.
2. Determine the physical processes by which plasmaspheric ion inflow influences horizontal neutral mass flow.

TABLE D-5 Science Traceability for the SOURCE+ Mission

Science Objectives	Measurement Objectives	Required Observables
1. Determine the physical processes of horizontal neutral mass flow that regulate ion upwelling and outflow.	Determine the horizontal spatial variability of vertical outflow. Determine the horizontal neutral mass flow of dominant species. Determine the altitude variation in the plasma upward flow distribution and the vertical ion mass outflows. Determine the large and midscale global currents. Determine the relationship between storm-enhanced density and plumes and ion outflow.	Ionosphere/thermosphere/mesosphere parameters between 350 and 1,500 km at 2 km spatial resolution: • Electron density • Electron temperature • Electric field magnitude and direction • Region 1 and 2 current flows • O and N_2 composition • Ion composition • 4D ionosphere density map
2. Determine the physical processes by which plasmaspheric ion inflow influences horizontal neutral mass flow.	Determine the horizontal spatial variability of vertical inflow. Determine horizontal neutral mass flow of dominant species. Determine the relationship between plasmasphere collapse and plasma flowing into the ionosphere. Determine the large and midscale global currents.	

As summarized in Table D-5, the SOURCE+ mission targets those ionosphere–thermosphere factors that lead to transport across the ITM boundary to the plasmasphere. An important aspect of magnetosphere–ionosphere–thermosphere boundary (PSGs 1.1 and 1.2) system science is to understand the distinction between upwelling (bound to Earth) and outflow that depends not only on magnetospheric acceleration processes but also on the neutral ambient atmosphere and current systems that are closed within the ionosphere. By having relatively coincident observations of magnetospheric outflow and ionosphere–thermosphere state parameters, SOURCE+ will be able to quantify the significance of magnetospheric coupling to and specific variability of the IT system (PSG 3.2).

Mission Configuration, Deployment, and Operations

SOURCE+ consists of two identical ~400 kg class satellites separate from those of the baseline SOURCE mission, each hosting four science instruments: Langmuir probe, ion neutral mass spectrometer, electric field probe, and GNSS radio occultation. They would be located in the same plane as SOURCE M1 and M2. Because SOURCE+ requires three-axis stabilized satellites for the science payloads to be fixed rather than spinning, they are denoted as M1F and M2F.

The baseline SOURCE mission instrument complement has limited resolution capability and parameter measurement for ITM region plasma dynamics characterization. Specifically, it is important to observe ITM vector electric and magnetic fields at a high resolution. Accordingly, SOURCE+ has a 16 Hz sampling rate versus the original 6 Hz. Furthermore, heavy neutrals are important at the exobase, but the baseline mission is limited to hydrogen from a Lyman-α imager. SOURCE+ will provide in situ observations of multiple heavy neutral species providing a more complete specification of species and their smaller scale variability; both are required to understand the spatial variability of upwelling and outflow.

The two SOURCE+ satellites would be launched along with the M1 and M2 SOURCE vehicles into 350 by 1,500 km elliptical orbit. M1F and M2F would follow the M1 and M2, respectively.

While there are no requirements for specific ground observations to meet SOURCE+ science goals, the science returns will be significantly enhanced with coordinated ground-based observations. The inclusion of IS radar observations at high and subauroral latitudes will provide quantified inflow/outflow drivers and rates. TEC maps derived from high-density GPS ground networks will localize the plasmasphere boundary layer and enable ionospheric mapping of the dusk sector plasmaspheric plume structures transporting ionospheric O^+ to the dayside magnetopause. Last, magnetometer data such as the Canadian Array for Realtime Investigations of Magnetic Activity (CARISMA) can be used or assimilated for field-aligned current location, magnitude, and dynamics.

Baseline Mission and Possible Descopes

SOURCE+ is an augmentation to the magnetospheric centric SOURCE mission and has no potential descope option. All instruments have significant flight heritage, minimizing any development cost. The satellite design including several instruments is similar to the successful C/NOFS mission, thus minimizing design and operational risk.

Expected Outcomes

The SOURCE+ concept provides the capability to conduct system science across the coupled magnetosphere and ITM regions, thus representing a significant scientific-value addition to the baseline SOURCE mission. SOURCE+ addresses questions of mass transport across the boundaries of these two regions (PSG 1) as well as the implications and impacts of that transport on the composition of the ITM (PSG 2). The mission synergizes with GNSS ground network observations of plasma content. The mission will have broader implications for what types of atmospheric evolution processes might lead to persistent changes (PSG 4), and more broadly, to refining requirements for habitability, possibly even beyond the solar system in the study of exoplanets.

D.6.3 Ground-Based Facilities

As with spaceflight mission concepts, the panel identified five specific ground-based facility implementation concepts that provide critical measurements of key state parameters needed to understand the ITM as a holistic system. Because the diversity and complexity in ITM science precludes the notion of any single all-encompassing concept or a strictly descending priority order of implementation, the ground-based facility concepts in this section are not presented in a ranked order.

DASHI: Distributed Arrays of Scientific Heterogeneous Instruments

Implementation strategy: Develop and provide sustained support for a distributed network of at least 30 autonomous observing stations across North and South America, with each station hosting identical heterogeneous instrumentation for simultaneous measurement of winds, temperatures, and electrodynamic parameters from ~80–400 km altitude.

As an NSF Major Research Equipment and Facilities Construction (MREFC)-class facility, the DASHI concept provides continuous and distributed observations of key ITM state parameter fields—plasma and neutral density, composition, temperature, and velocity—and their spatiotemporal evolution on multiple scales, thereby enabling transformative advances in understanding the ITM as a coupled system. This comprehensive characterization of ITM composition, energetics, and dynamics is achieved through the coordinated, ground-based deployment of networked, heterogeneous sensors, which together constitute the distributed facility known as DASHI. The baseline sensor selection and placement are designed to provide sufficient spatial (vertical and horizontal), temporal, and measurement resolution and span to allow evaluation of the derivative terms in the continuity, momentum, and energy equations which govern ITM system behavior. The DASHI concept extends the spatial coverage of current ground-based sensor arrays across the geophysically rich longitude sector spanning North and South America, transforming present-day, ad hoc sensing approaches into strategically planned deployments needed for diverse system science investigations.

Unlike the space mission concepts presented in Section D.6.2, the DASHI facility is not designed to focus on a specific science objective; rather, implementing the notional network described here would enable significant progress toward all four ITM PSGs identified in Section D.3. Specifically, DASHI's dense, continent-wide coverage provides unprecedented views of large-scale ITM field conditions, such as background atmospheric circulation patterns. It will also simultaneously observe embedded mesoscale structures, such as gravity waves, ionospheric "superbubbles," and TIDs and TADs. Such comprehensive observations are critical for understanding how various perturbations in the equilibrium ITM state originate, propagate, and dissipate, particularly regarding the roles of preconditioning, feedback, and cross-scale coupling in mediating these dynamics (PSGs 1.2, 2.3, 2.4, and 3.1). With sensor network nodes spanning latitudes from the Arctic to the Antarctic, DASHI is well suited to observe potential hemispheric asymmetries in mesoscale ITM structures and their spatiotemporal evolution (PSG 3.4). Dedicated operation of DASHI sensors supports the routine detection of a wide variety of extreme impulsive forcing events, such as volcanic eruptions and geomagnetic storms as well as near-continuous monitoring of their evolution and impact on the ITM system (PSGs 1.1 and 3.3).

A key feature of the DASHI concept design is its observation of the spatial distribution of vertical neutral winds, a particularly long-standing measurement gap. Vertical winds modify thermospheric composition and can vary strongly over horizontal scales as short as a few hundred km or less; as a result, their continuous measurement on dense regional scales is vital for understanding the origin of day-to-day variability (PSG 3.2). Meanwhile, sensor heterogeneity at each DASHI network node is designed to provide height-resolved observations of coupled ITM state parameters, as these data are critical for understanding how forcing from the lower atmosphere, especially associated with gravity waves, is transmitted throughout the ITM (PSGs 1.3, 1.4, and 2.1). The diversity of ITM state parameter measurements that each DASHI station will provide, along with long-term temporal continuity through facility-level investment and operation, enables an assessment of the impact of ongoing (and accelerating) evolution in ITM system drivers, particularly anthropogenic changes in ITM composition (PSG 4.2). As notionally defined below, DASHI will extend the existing, decades-long, temporal baseline of several key ITM state parameter databases, enabling more accurate detection of slow system evolution as well as potentially abrupt transitions in ITM equilibrium conditions (PSGs 4.1 and 4.3).

The obvious scientific benefit of a distributed, ground-based observing network has been recognized for decades in numerous strategic planning documents. The concept was among the programs recommended in the 2013 decadal survey and has since been endorsed in the 2006 report of a workshop on *Distributed Arrays of Small Instruments for Solar-Terrestrial Research* (NRC 2006), the 2015 National Space Weather Action Plan (NSTC 2015), the 2016 NSF Geospace Portfolio Review (NSF 2016), and the 2013 decadal survey, which specifically recommended the following:

> Develop, deploy, and operate a network of 40 or more autonomous observing stations extending from pole to pole through the (North and South) American longitudinal sector. The network nodes should be populated with heterogeneous instrumentation capable of measurements including winds, temperatures, emissions, scintillations, and plasma parameters, for study of a variety of local and regional ionosphere–thermosphere phenomena over extended latitudinal ranges.

Over the past decade, NSF's peer-reviewed DASI program has supported several regional, PI-led, networks of ground-based sensors, including magnetometers, all-sky imagers, Fabry-Pérot interferometers, ionosondes, radio receivers, and meteor radars. Numerous other ground-based sensors are supported outside the DASI program, either as ancillary instrumentation at Class 1 IS radar facilities; as stand-alone Class 2 facilities (e.g., Super Dual Auroral Radar Network [SuperDARN], Active Magnetosphere and Planetary Electrodynamics Response Experiment [AMPERE], and SuperMAG); or as small, PI-led, sensor development and deployment projects supported through programs like CEDAR, CAREER, or core NSF Aeronomy. While highly successful individually, neither facilities nor PIs who operate single-sensors or single-sensor networks are well coordinated with each other with regard to operational planning (deployment and data acquisition strategy, common volume sensing, etc.), sensor cross-calibration, or joint data analysis. As a result, investigations of ITM processes using these assets are typically conducted in isolation and thus fall short of providing the comprehensive characterization of coupled ITM state parameters needed to address the next decade's PSGs. Additionally, many existing assets are typically undersupported, undermaintained, and often deteriorating, putting the scientific utility of long-term data sets at risk.

It is emphasized that the concept of DASHI as a distributed facility complements, rather than replaces, continued NSF support for existing facilities and ground-based sensors, which remain a vital part of overall strategy to address the priority science objectives described earlier. Implementation of a new heterogeneous sensor network would strongly benefit from leveraging both the instrumentation and supporting infrastructure—such as ease of access, electric power supply, and internet connections—that is available at currently operating ground-based sites, which are primarily distributed across North and South America. Although a dense, globally distributed sensor array would provide the ideal spatial coverage in support of ITM system science investigations, the less ambitious DASHI concept described here represents a "first step" whose implementation over the next decade is more feasible. To that end, current IS radar facilities are particularly well suited as DASHI network nodes, not only because they already host a suite of critical ancillary instruments and can more easily accommodate expansions in hosted instrumentation, but also, and most significantly, because their precise, height-resolved, local ionospheric specification (see "Subauroral IS Radar," below) provides unique and valuable constraints on DASHI data analysis, particularly during coordinated "World Day" campaigns. These sites also have long-term, multiple solar-cycle observation records that will further aid scientific analysis (see PSG 4).

A depiction of a notional DASHI network of 30 observing stations, including existing SuperDARN nodes, is depicted in Figure D-22. This configuration is intended to be illustrative, not prescriptive, and OSSE modeling studies are needed to determine the optimal number and location of DASHI sites in terms of balance between

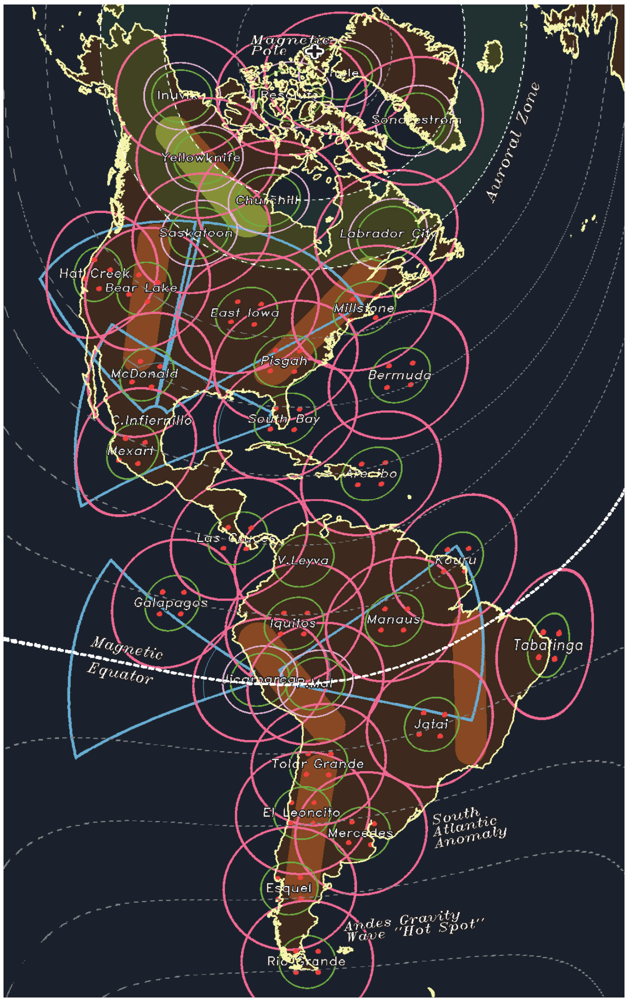


FIGURE D-22 Fields of view of the proposed DASHI observatories and instruments.
NOTE: Pink and green circles (projection distorted): ground-based cameras imaging at 630 nm and 558 nm; four red dots: narrow-field Fabry-Pérot interferometer sampling; lilac circles: Scanning Doppler Imager field of view; blue wedges: SuperDARN field of view; orange/green shading: multistatic meteor radar field of view; dashed contours: magnetic latitude.
SOURCE: Conde et al. (2022), https://doi.org/10.3847/25c2cfeb.593c3238. CC BY 4.0.

sensing requirements and available resources. The physical implementation of a distributed ground-based sensing array would benefit from standardization in the fabrication and deployment of both the individual sensors as well as the shared observing platform. For example, commercial 8 feet × 20 feet shipping containers are easily customizable, deployable, and relocatable, providing low-risk, shovel-ready construction.

Unlike single-sensor networks, DASHI is designed to provide a comprehensive, height-resolved, characterization of the local ITM state at each network node via common-volume sensing by heterogeneous instrumentation. A notional list of state parameters and associated sensors, designed to enable simultaneous characterization of winds, temperatures, and electrodynamics in a region spanning altitudes ~80 km to ~400 km, is given in Table D-6. Note that this representative configuration includes a meteor radar and GNSS receiver at each DASHI station; a network of meteor radars, which is required for science closure on the BRAVO mission, is described as a standalone concept in the section "Meteor Radar Network" below, and an extension of the GNSS network beyond the American longitude sector is described as a standalone concept in the section "Extended GNSS Network" below. The illustrative description of the DASHI concept provided here is just one example of a heterogeneous sensor array that would offer transformative advances in all four of ITM's PSGs as described above. Different sensor configurations also would be scientifically productive in meeting these goals. A community-led effort, supported by OSSE modeling, is needed to determine instrument selection and implementation phasing, and it is premature for the ITM panel to prescribe these details in this report.

Another key aspect of the DASHI concept implementation is its facility-based management structure, intended to streamline technical, logistical, and regulatory tasks. Dedicated management support is particularly important for coordinating data product development and archiving, as these form a critical prerequisite for data assimilation in

TABLE D-6 Notional List of DASHI Facility-Supported Instrumentation

Instrument/Parameter	Field-of-View	Typical Resolution	Uncertainty
SDI/wind & temp @ h=120 km	Circular, Ø750 km	H:60 km, t:2–20 min	±5 m/s; ±10 K
SDI/wind & temp @ h=240 km	Circular, Ø1400 km	H:115 km, t:2–20 min	±5 m/s; ±20 K
FPI/wind & temp @ h=240 km	NESW @ 45°	H:500 km, t:2–30 min	±5 m/s; ±15 K
All-Sky Imager/840 nm intensity	Circular, Ø520 km	H:2 km, t:10 sec	±1% relative
All-Sky Imager/558 nm intensity	Circular, Ø600 km	H:2 km, t:10–240 sec	±1% relative
All-Sky Imager/630 nm intensity	Circular, Ø1400 km	H:2-4 km, t:10–240 sec	±1% relative
All-Sky Imager/589 nm intensity	Circular, Ø600 km	H:2 km, t:10–240 sec	±1% relative
AMTM/Temperature @ h=87 km	Rectangular, 180×144 km	H:600 m, t:30 sec	±2 K
SuperDARN/Plasma velocity	Fan, 54°×3599 km	H:45 km, t:2 min	±45
SIMO/Winds @ h=80–100 km	Circular, Ø400 km	V:2 km, t:1 hour	±2 km
MIMO/Winds @ h=80–100 km	Elongated, 400×2400 km	H:15 km, V:1 km, t:30 min	±15 km
GNSS RX/TEC, Scintillations	Circular, 150° full-angle	t:1 Hz TEC; 50Hz Scint	±1%
Magnetometer, B-field variations	Local	t:1 sec	±1 nT
Ionosonde/Elec Den @ 80–400 km	Vertical Profile	t:15 min	Varies

NOTE: AMTM, Advanced Mesospheric Temperature Mapper; DASHI, Distributed Arrays of Scientific Heterogeneous Instruments; GNSS, Global Navigation System Satellite; MIMO, multistatic meteor radar; NESW, North, East, South, West; SIMO, monostatic mesospheric meteor radar.
SOURCE: Conde et al. (2022), https://doi.org/10.3847/25c2cfeb.593c3238. CC BY 4.0.

support of more accurate space weather forecasting as well as underpinning strategic system science investigations. Support for dedicated DASHI facility scientists is also vital to ensure routine and accurate sensor intercalibration as well as appropriate community data usage, including provision of study methodologies, which are not only science productive but also give direct examples of how to effectively employ DASHI observations.

In summary, DASHI provides a comprehensive ensemble of coincident, common-volume, and distributed ITM state parameter measurements that are needed to understand numerous aspects of the ITM as a dynamical system that is strongly coupled to the overall geospace system-of-systems. DASHI will reveal the underlying physics governing the variable ITM state (e.g., electrodynamics, ion-neutral momentum and energy exchange, and transport within and across ITM transition regions) without the ambiguity that arises from "missing a term" in the governing equations through lack of observational constraint.

DASHI will not only significantly expand fundamental scientific knowledge, but it will also provide a vital observational resource for physics-based model validation and refinement as well as for data assimilation in support of more accurate space weather forecasting capabilities. DASHI also directly supports MAG science priorities by providing coincident, common-volume observations of magnetosphere–ionosphere–thermosphere coupling across the high-latitude Northern and Southern hemispheres. DASHI ground-based characterizations are relevant to many in situ missions by virtue of their extended coverage in space and time, in a manner unavailable from single-satellite platforms in LEO. Selection, implementation, and operation of the DASHI science products is best evaluated jointly with current and future community needs to enhance the science return of space-based missions and other ground-based facility products.

Meteor Radar Network

Implementation strategy: Develop and provide sustained support for a meteor radar network with global coverage, including a continent-scale region with dense multistatic capability, to simultaneously measure parameters of gravity waves and meso- to global-scale atmospheric waves.

Characterization of the neutral atmosphere, in particular neutral winds, has been repeatedly identified as a crucial observational gap that must be addressed to advance knowledge of the coupled ion-neutral processes governing upper atmosphere dynamics. In previous decades, many meteor radar systems have been deployed and operated, at global locations but mostly independently, to provide local observations of the neutral wind from ~80 to ~100 km altitude, derived from Doppler shifts of sporadic meteor trail scatter. Stand-alone "monostatic" single-site systems have provided near-continuous monitoring of a single wind profile, representing the vector wind horizontally averaged over the field of view (~200–300 km) and temporally averaged in post-processing (typically a 15- to 60-minute window). These data have produced important insights into tidal and planetary wave activity in a large number of studies. However, progress on comprehensive multiscale wind field information from these observations (quantities of compelling interest to gravity wave and whole atmosphere modeling work) is inherently limited, because single sites cannot distinguish migrating from nonmigrating tides and cannot resolve small-scale waves. Some studies have attempted to address this through combined data from longitudinally separated sites, in order to resolve sampling ambiguities and estimate nonmigrating tides and planetary waves. There have also been some efforts to strategically deploy networks of monostatic sites (e.g., the Chinese Meridian Circle Project). However, a dedicated deployment of wind radars capable of simultaneously observing small and global scales would be transformative in its ability to truly characterize the lower boundary wave forcing of the ITM (relevant to PSG 1) and to more fully address cross-scale coupling (PSG 2).

In recent years, technological advances have led to networked deployments of multistatic, multiple-input/multiple-output (MIMO) radars, which use large-count sporadic meteor trail reflections to resolve features within the field of view. Initial deployments have achieved regional coverage (~500 × 500 km) and enabled 4D wind field estimates with resolution around 30 km horizontally, 3 km vertically, and 15 minutes temporally, with low operating costs. Figure D-23 shows an example wind field estimate that reveals significant mesoscale structuring. Statistical information on the spectrum of unresolved waves can also be extracted. Several small pathfinder and/or campaign deployments have been successful in Europe and the Americas, providing evidence for high feasibility. Addressing the PSGs for the next decade would benefit from increased global coverage over a continent-scale

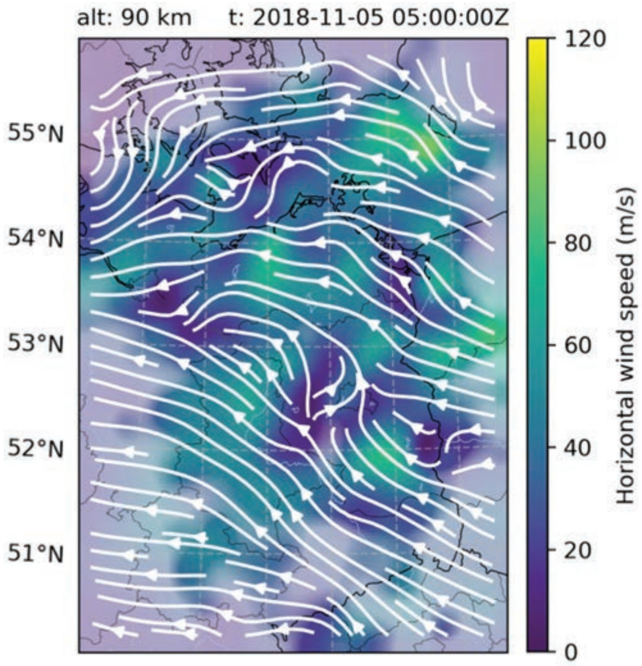


FIGURE D-23 A snapshot of a wind field at 90 km altitude, estimated using data from the Spread spectrum Interferometric multistatic Meteor radar Observing Network (SIMONe) campaign in Northern Germany. Streamlines display the direction of the horizontal neutral wind flow, with color representing the magnitude. Transparency indicates low confidence owing to low meteor density.
SOURCE: Volz et al. (2021), https://amt.copernicus.org/articles/14/7199/2021. CC BY 4.0.

region featuring dense multistatic capability, implemented as an NSF Mid-scale Research Infrastructure (MSRI)-2 (at a minimum).

A multistatic meteor radar network is already a required element of the BRAVO mission concept described earlier, and it would support other space-based missions and existing ground-based facilities. For GDC/DYNAMIC, it would provide lower boundary inputs not directly observable by GDC, and potentially would probe smaller scales than observable by DYNAMIC with better local-time sampling than possible from LEO. It is likewise directly synergistic to the Resolve mission's focus on larger-scale waves.

In addition to complementing space-based investigations, a stand-alone multistatic network would enable independent progress on all four PSGs. Such a network would directly address PSG 1.3 by providing a comprehensive characterization of the atmospheric wave spectrum at the ITM lower boundary. It would also directly address cross-scale coupling of atmospheric waves (PSGs 2.1 and 2.3) by providing the first mesoscale observations of spatial and temporal variability in the MLT with regional coverage. Because these scales cannot be simultaneously observed in a straightforward manner using alternative techniques, this facility will support unprecedented studies of wave/wave and wave/mean-flow coupling. This network would support studies of day-to-day variability of the ITM (PSG 3.2) by characterizing the gravity wave spectrum needed to quantify its role in driving mesospheric and thermospheric weather. A reinvigorated meteor radar observational capability would also support PSG 4 by supplementing and extending the historical meteor radar network and beginning to establish long-term observations of daytime and nighttime gravity wave dynamics. Providing vital constraints on lower atmosphere drivers would support more accurate space weather forecasting by enabling near-real-time data assimilation, never before available in this configuration.

An OSSE will need to be conducted to determine the optimal distribution, density, and design parameters for the sites. Deployments in foreign countries can be logistically complex, so efforts can be made to partner with existing international sites. If budgets do not allow for global coverage, a descope option is to focus only on mesoscale structure, not global structure, and deploy a stand-alone dense continent-scale network, which may be commensurate with NSF's Mid-scale Research Infrastructure program.

Subauroral IS Radar

Implementation strategy: Develop, deploy, and operate a new modern IS radar facility, including supporting ground-based instrumentation, in the subauroral latitude region to enable simultaneous characterization of ionospheric, thermospheric, and plasmaspheric state parameters during both quiet and storm-time conditions.

Incoherent/collective Thomson scatter radar remote sensing has long been recognized as an extremely powerful means of measuring fundamental state parameters of the ionosphere and inner plasmasphere. IS radars provide direct, height-resolved, measurements of electron density, ion and electron temperature, ion composition, and line-of-sight plasma drift velocities with quantified parameter uncertainties, and the use of multiple radar beams enables vector velocity measurements on regional scales. In conjunction with ancillary models, the IS technique also supports inferences regarding ionospheric conductance, Joule heating, electric current systems, electron energy distributions, and neutral winds. IS radar data has been vital for advancing understanding of the ITM system through its role in countless ground-based investigations. In addition, IS radars are routinely used to support space-based missions and to interpret observed GNSS scintillation driven by space weather.

The design space for IS radars is notoriously large, and the diverse capabilities of the four radars in the current Geospace Facilities portfolio reflect the different scientific priorities of the eras in which they were designed. Following the decommissioning of the Arecibo Observatory and Sondrestrom Observatory this past decade, the current portfolio still includes two of the original IS radars, the Millstone Hill Geospace Facility and Jicamarca Radio Observatory. Although continual upgrades have served to maintain their formidable capabilities, both are based on less sophisticated radar designs of the 1960s, when questions about geospace were relatively naive. Furthermore, many of their design parameters were not driven primarily by geospace research needs. The AMISR-class phased array radar designs of the 1990s and early 2000s, which support electronic rather than physical steering of the radar beam, have enabled PFISR and RISR-N to significantly advance understanding of high-latitude plasma dynamics. However, both were implemented using now-obsolete components with limited availability and are approaching the end of their planned 20-year operational lifespan.

Continued investment in the operation and maintenance of these existing radars is critical for addressing priority ITM science goals in the coming decade, because each provides a unique and irreplaceable characterization of the ionospheric state and its variability under diverse geophysical conditions, from the polar cap to the equator. In particular, these facilities have produced a long baseline of calibrated ionospheric data over the past several decades, and their continued operation is ideally suited for detecting both secular trends and sudden state transitions in support of ITM PSG 4.

Beyond current facilities, significant additional benefit to ITM science would be achieved by expanding the NSF Geospace facility portfolio to include a new MREFC-class IS radar facility, whose state-of-the-art design would leverage recent worldwide innovations in radio astronomy and radar techniques and enable unprecedented resolution, spatiotemporal coverage, and operational flexibility. Modern capabilities of the new IS radar facility will include

- Electronic steerability of multiple radar beams simultaneously, which would offer a significant advance over current single-beam capabilities of the AMISR-class radars.
- Multistatic observations, where multiple receivers are sited away from the radar transmitter to enable instantaneous and continuous (e.g., nonsteered) measurements of the vector plasma drift velocity digital interferometric imaging via spaced receiver arrays, which would detect plasma structure and coherent plasma features within the beam at higher spatial resolution than current AMISR-like beam steering supports.

- MIMO capability, in which distinct waveforms are transmitted by subdivisions of the array to exceed the theoretical angular resolution limits of standard experiments.
- Broadband reception, which would enable passive sensing at multiple radio frequencies (thus directly determining multiscale plasma response, turbulent cascade, and dispersion relation characteristics) in addition to active radar sensing.

While a new IS radar facility with these state-of-the-art capabilities would greatly advance ITM science at any latitude, its deployment in the subauroral region would make it particularly well suited for addressing numerous science objectives that are strategic priorities for the coming decade. The subauroral ionosphere exhibits a large variety of multiscale plasma phenomena involving both aeronomical and electrodynamic processes, particularly during storms.

For example, the inner magnetosphere and subauroral ionosphere tightly couple through downward field-aligned heat conduction and upward ion upwelling/outflows. A modern IS radar in this location would directly address PSG 1.2 by measuring complete profiles of plasma density and temperature along a field line, allowing for the evaluation of ion pressure gradients, ambipolar electric fields from electron pressure gradients, electron heat fluxes from electron temperature gradients, and ion upflow fluxes along the field line.

When operating in the low VHF band, a modern IS radar would be also able to measure volumetric ion velocity and thus observe the interplay of gravity waves, stratified turbulence, and mean and tidal flows, providing crucial constraints on their vertical coupling during different seasons in support of PSGs 1.3 and 1.4. Meanwhile, the multiple radar beams, multistatic sensing, and digital interferometry capabilities of a modern IS radar would enable the detection of plasma structuring at unprecedented spatial resolution and temporal continuity. Such capabilities are ideally suited for investigating diverse subauroral plasma phenomena at all spatial scales, specifically: (1) medium- to large-scale (~100–1,000 km) density gradients associated with the plasmasphere boundary layer, the midlatitude trough, SAPS, SAR arcs and ring current coupling, and storm-enhanced density (SED) plumes; (2) mesoscale (~10–100 km) subauroral ion drifts and STEVEs; and (3) small-scale (100–1,000 m) density gradients and velocity shears, which drive plasma instabilities. Such measurements are critical for addressing PSGs 2.1, 2.2, 2.4, 3.1, and 3.3.

Extended GNSS Network

Implementation strategy: Upgrade existing surface-based GNSS receiver infrastructure and expand the network into the low-latitude oceanic and African areas to produce continuous worldwide TEC and distributed GNSS scintillation measurements.

From imaging the planetary redistribution of ionospheric plasma during geomagnetic storms to showing the upward coupling of perturbations owing to the Hunga Tonga eruption into the upper atmosphere, GNSS-based measurements of integrated ionospheric electron content have grown indispensable for ITM researchers over the past couple of solar cycles. And all the evidence of chemical and dynamic forcing and coupling over a wide range of TEC sensitivity to date has been found primarily from leveraging other organizations' publicly, continuously available multifrequency GNSS data opportunistically, for ionospheric sensing rather than the positioning, navigation, and timing that GNSS was designed for. Many of the GNSS networks worldwide use geodetic receivers, and while useful and now providing a multi-solar-cycle record of TEC, these networks are not yet optimized for ITM science.

GNSS TEC measurements are essential for numerous ITM and plasmaspheric studies. They are widely used for global horizontal ionospheric characterization at ~100 km scales. Observations yield important information on plasma-neutral coupling effects of neutral winds and waves/tides. Plasmaspheric plume boundaries are electrodynamically coupled along magnetic field lines to ionospheric structures clearly visible in TEC, such as storm-enhanced densities (SEDs). Differential TEC data are a very sensitive detector of ionospheric wave activity (TIDs). Global coverage provides multiscale information not fully replicated by GNSS satellite-borne receivers.

GNSS derived scintillation indices and high-rate 50 Hz measurements are also widely used, although data are orders of magnitude less plentiful than TEC measurements. GNSS scintillation-capable receivers directly sense instabilities in generating regions such as equatorial density depletions/bubbles at L band–scale sizes (~300 m). At high latitudes, scintillation is evidence of magnetosphere–ionosphere electrodynamic and particle inputs that produce fine-scale irregularities.

The high scientific value of TEC and scintillation products is not matched by ITM-specific investments. To date, ITM has obtained ground-based GNSS TEC opportunistically from other user communities' receiver networks (e.g., geodetic), without dedicated operational investments. As a result, there are limitations of current capabilities in spatial extent, horizontal resolution, and temporal cadence. These networks do not currently cover oceans, which renders the longitudinal evolution of ionospheric features unobservable, a difficulty particularly troublesome for low-latitude longitude sector studies. A data gap also exists in the African subcontinent. Ionospheric structures from processes that cross all latitudes such as SEDs become "invisible" when entering and exiting these gaps, removing the ability to study the important magnetic local time and longitude dependence of these processes. The publicly available non-ITM network receivers are nearly all sited on tens of km to hundreds of km baselines, which yields a comparable horizontal resolution of ionospheric structures. Very few receivers are as closely spaced as on a ~1 km baseline, although ionospheric structures can reach this scale size, such as in auroral bands, which can produce scintillation at high latitudes. Another limitation of publicly available GNSS products is that they are often at only 30-second to 1-minute cadence, whereas tens of Hz sampling is required to characterize scintillation.

ITM has not had a dedicated GNSS network facility to date, although there have been individual PI-led investigations—for example, LISN as a DASI Track 2 award, the Scintillation Auroral GPS Array (SAGA), and the Multicenter Airborne Coherent Atmospheric Wind Sensor (MACAWS). Each of these networks has spanned a different spatial extent (1, 10, and hundreds of km), and each has included investment in dedicated scintillation receivers, which are not of interest to geodetic or surveying communities and therefore not systematically invested in by other groups. Specialized GNSS receivers obtain both TEC and scintillation indices, which gauge the presence of irregularities at tens of centimeter scale, as well as the detrended signal power and phase output at ~50 Hz, measuring irregularity scale cascade.

While alternative techniques for sensing TEC in geographical gap areas exist—for example, from VLF measurements of lightning—these would require regular access to data derived from the VHF transient-sensing systems on board the Department of Defense GPS satellites.

The proposed dedicated ITM science GNSS network, implemented as at least an NSF MSRI-2 class initiative, would provide surface-based TEC and scintillation measurements in large data gap regions. The receiver platforms would constitute a distributed surface facility with land- and sea-capable nodes. For oceanic sites, passive or active station-keeping platforms would be needed (buoys or sail drones). The required spatial coverage/resolution determines the science investigations that can be undertaken, but a lower horizontal bound of about 300 m (Fresnel scale of GNSS) to up to ~100 km would enable TID imaging. GNSS are low-power receivers that are always on, day and night, independent of cloud cover and local weather conditions. Avoidance of solid obstructions of the sky (tree canopy, buildings, etc.) and low-latency or ideally real-time data products are desirable.

The ionosphere is a unique "projection screen" on which much of ITM behavior could be relatively easily sensed. For this reason, data from a dense GNSS network addresses multiple PSGs as follows:

- *PSG 1.2:* A GNSS network gauges ionospheric effects of precipitation from magnetospheric sources. GNSS monitors the development and evolution of ionospheric instabilities through the monitoring of scintillation.
- *PSG 2.4:* Scintillation receivers are sensitive to irregularities at ~300 m scales. Distributed arrays are sensitive to variations (waves, TIDs) at scale length proportional to the array spacing.
- *PSG 3.1:* TEC and scintillation are end observables that test which causal mechanisms have been effective at driving ionospheric structure changes.
- *PSG 4.1:* GNSS observations are uniquely suited to provide continuous global higher spatial and temporal resolution of ionospheric conditions. GPS/GNSS observations have been present and widespread for global imaging of TEC for more than 2 solar cycles already.

A surface GNSS TEC plus scintillation network is synergetic with magnetospheric physics at high latitudes, where magnetosphere–ionosphere coupling manifests as enhancement in TEC (patches, precipitation) and turbulence that gives rise to GNSS scintillation. Changes in solar radiation directly affect ionospheric production in ways that are most readily visible at the solar terminator and during solar eclipses. Ground-based TEC gauges these changes in solar UV output in a synoptic and multiscale way. Scintillation forecasts are of great interest for space weather communications and navigation. Providing this data, and in near real time, would help support operators' decision-making needs. GNSS networks are a plentiful data source that have been used for model validation and assimilation. Resilient space weather forecast applications need to assimilate data consistently from a dedicated network that is not solely reliant on data from publicly available networks that may not always remain available. The BRAVO and SOURCE+ and other missions will be enhanced by the synoptic multiscale ionosphere/plasmasphere state information available from GNSS TEC.

LiDAR Facility

Implementation strategy: Develop and provide sustained support for a high-power-aperture LiDAR facility capable of obtaining continuous altitude profiles of temperature, composition, and winds from 60 to 1,000 km altitude.

LiDAR instruments have seen rapid technology development in the past decade, from solid-state lasers to improved range distances. LiDAR is an important remote sensing technique that can derive critical profiles of temperature, density, composition (both neutrals and ions), and winds. Important insights into wave propagation and breaking, density of metals of meteoric origin, and the background state of the mesosphere and thermosphere have been found. However, current facilities in the U.S. portfolio are limited to reaching altitudes of up to 140 km, use telescopes that are less than 3 meters in diameter, have power that is limited to a few watts, employ non-solid-state lasers (touch-intensive and sensitive liquid dye lasers are in frequent use), and they are typically not transportable. Notably, other nations such as China have made significant investments in their LiDAR technologies, resulting in exciting new developments in ITM science such as extending the altitude reach of their instruments and detecting new species.

With the significant advances in LiDAR technology, it becomes possible to develop a cutting-edge, transportable LiDAR facility. Such a facility would host co-located Rayleigh, Na, Fe, and He LiDARs, which would likely require an NSF MREFC-scale investment. This combination of LiDARs would provide height-resolved profiles of neutral temperature, composition, and winds from the stratosphere into the exosphere near 1,000 km, which is a factor of 10 improvement. This new capability would provide the first routine measurements of winds and temperature across Earth's exobase, which directly governs hydrogen escape and exospheric structure, knowledge of which is critical for understanding ionosphere–plasmasphere coupling and energy dissipation during geomagnetic storms. This technology would leverage a large power-aperture (11 m) optical telescope array (OASIS 2014). This facility is meant to be transportable between desirable sites and potentially co-located with other instruments such as IS radars to expand the potential science return.

The LiDAR facility concept builds on the 2013 decadal survey AIMI panel suggestion, "Create and operate a LiDAR facility capable of measuring gravity waves, tides, wave–wave and wave–mean flow interactions, and wave dissipation and vertical coupling processes from the stratosphere to 200 km." In the context of the new PSGs, a modernized large LiDAR facility would address PSGs 1.3 and 1.4, which examine the ITM response to external forcing and the transition in governing physics within the mesosphere and lower thermosphere. Additionally, it would address PSGs 2.1 and 3.2, which investigate cross-scale coupling of waves and the origin of short-term (day-to-day) variability. Example science questions to be addressed include

- What are the vertical fluxes of momentum, heat, wave energy, and constituents in the stratosphere and mesosphere below 80 km and in the lower thermosphere above 100 km?
- How are stratospheric ozone dynamics affected by wave transport of nitric oxide (NO) downward out of the thermosphere into the mesosphere and stratosphere?
- Where is the turbopause in Earth's atmosphere? How does it vary and how is it related to local wave activity and the subsequent processes influencing the limiting flux of escaping hydrogen?
- How does turbulence affect plasma/neutral coupling and large-scale flow?

- What are the dynamical and thermal effects of breaking waves, and how do they impact atmospheric circulation? (See Figure D-24.)
- How do neutral temperatures and winds near the exobase change in response to geomagnetic storms?

An Observatory for Atmosphere Space Interaction Studies (OASIS)-type LiDAR facility would employ modern solid-state laser technologies to increase the output powers by a factor of ~10 and a large array of fiber coupled telescopes to increase the aperture area by a factor of ~100 (OASIS 2014). There are multiple areas for synergy with other heliophysics disciplines and missions. For example, this type of modern LiDAR facility data would provide a comprehensive ensemble of neutral ITM state parameters that are vital for validating physics-based models and informing their continued development, and characterization of the small-scale wave spectrum will help to define lower atmosphere drivers useful for space weather forecasting. In terms of notional missions, both BRAVO and LAITIR would benefit from conjunction measurements for additional science and calibration/validation studies. Locating the LiDAR facility near an existing (or new) IS radar would provide enhanced science return.

D.6.4 Other Observational Platforms

The preceding two sections describe concepts for large space-based missions and ground-based facilities that would each enable significant progress toward addressing many of the scientific objectives in support of ITM's PSGs in the coming decade. However, the panel also recognizes the significant potential for other observational platforms, such as single, PI-led sensor deployment, to provide unique and valuable measurement constraints. The individual implementation strategies described in this subsection are important elements of a cohesive strategy that is necessary to address the ITM PSGs within a system science paradigm in the next decade. Together with the other strategic components presented in Section D.5, they will result in a Heliophysics System Observatory (HSO) that would benefit generations of scientists and significantly improve understanding of the role of ITM in the geospace environment.

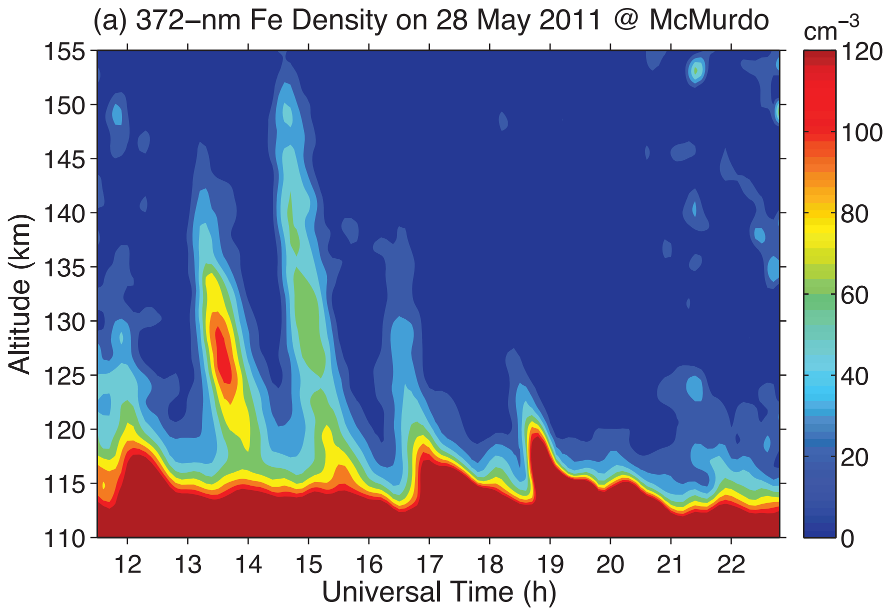


FIGURE D-24 Event on May 28, 2011, at McMurdo, Antarctica, of thermospheric Fe densities from 110 to 155 km, showing fast gravity waves in the thermosphere.
SOURCE: Chu et al. (2011).

Implementation strategy: Reconfigure resource allocation to prioritize strategic contributions to HSO and emphasize potential to advance ITM system science.

Implementation strategy: Establish more comprehensive, higher spatial resolution, and continuous monitoring of salient ITM state parameters.

Implementation strategy: Prioritize coordinated deployment and operation of heterogeneous sensors and distributed ground- and space-based platforms to support ITM system science investigations.

Implementation strategy: Prioritize the deployment of ground- and space-based sensors that extend the existing temporal baseline of ITM state parameter measurements, enabling detection of persistent changes in the geospace environment.

In aggregate, these four strategies address all four PSGs. Tackling those goals requires some combination of spatial and temporal multipoint observations of multiple state variables to establish contextual/multiscale conditions. Obtaining multiple state variables over a continuum of altitudes at globally distributed locations, as required for system science investigations, can be achieved only through a combination of sensor types. Most of the specific large spaceflight and large ground-based facilities described in previous sections focus on either specific state variables and processes located at single points (i.e., ground facilities) or limited spatial (altitude and horizontal) coverage from orbit. In isolation, these are inadequate to make progress in understanding the fundamental physical processes underlying ITM system science at *all* spatial and temporal scales.

Currently, there are few long-term, continuous, and well-calibrated state parameter data sets available for community studies of long-term trends or shorter-term systemic changes. The ionosonde database is the longest and most comprehensive one available, but many of the stations have been closed and automatic scaling is not yet accurate enough for most studies. The few other available data sources originate in single discrete ground sites (e.g., IS radar) or long-term orbiting missions (e.g., TIMED), and are insufficient owing to the limited spatial observations or type of state variable observed. Furthermore, without regular maintenance and/or replacement, these limited data sets will become unusable, significantly setting back the ability to begin to address PSG 4. An expanded baseline of state parameters spanning the globe, including horizontal and vertical coverage, is necessary to distinguish short-term local changes from the system-wide persistent changes that are the focus of PSG 4. However, the need for expanded long-term measurements must be balanced with available resources. Thus, it is important that a cross-agency coordinated prioritization list be developed with community input to maximize global observations of ITM state variables.

To date, the ability to conduct system science investigations of ITM phenomena has been hampered by a resource allocation structure that implements disconnected ground-based programs and mission lines. Given limited and currently decreasing resources for individual ground and flight programs, the first task of a combined cross-agency and community plan is to determine the optimal combination of those key strategic components that yield the greatest contribution to the HSO. The resulting priority list will enable a coordinated plan among agencies that maximizes the contribution of facilities, experiments, tools, and missions, regardless of size and complexity.

Implementation strategy: Use hosted payload and rideshare opportunities to investigate the ITM system on Earth and other planets, including system response to solar flux and solar wind inputs.

As discussed previously in Section D.5.1, the utilization of unconventional capabilities to deploy space-based sensors for ITM science investigations represents an important emerging opportunity to acquire key ITM measurements that are highly synergistic with the more traditional large mission and ground-based facility implementation strategies. NASA's rideshare initiative, developed over the past decade in close coordination with commercial launch providers, has recently matured into a highly successful, cost-effective means of deploying small standalone missions, particularly in orbits that would be unattainable otherwise. An example is the Carruthers Geocorona Observatory, a NASA Heliophysics Science Mission of Opportunity that will share a deep-space launch to the Sun–Earth L1 Lagrange equilibrium point with the flagship IMAP mission in 2025, thus enabling continuous, wide-field imaging of Earth's extended exosphere for the first time.

Such hosted payload or rideshare opportunities offer the only means for performing comparative planetary ITM studies in support of the Long-Term Science Goal (Section D.4) within a limited resource landscape. Any future flagship mission to the outer solar system (such as a Uranus Orbiter or Interstellar Probe) is likely to use Jupiter for a gravity assist, which presents a rare opportunity for deploying a small rideshare spacecraft at Jupiter.

A small spacecraft in halo orbit around the Sun–Jupiter L1 Lagrange equilibrium point could provide crucial constraints on the solar UV flux and solar wind inputs to the Jovian ITM system simultaneously with remote sensing observations of the ITM response to those inputs, in direct support of the Long-Term Science Goal, Objective L.1. Several flight opportunities exist or are in the planning stages that could place small spacecraft at the Sun–Mars or Sun–Venus L1 Lagrange points for similar missions in support of Long-Term Science Goal, Objective L.2. NASA launches missions to Mars every 2 years when the flight geometry is optimal and has two missions to Venus currently under development (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy [VERITAS] and Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging [DAVINCI+]). Exploiting such deployment opportunities would ensure the long-term availability of measurements needed to advance understanding of the ITM response to solar drivers on planetary ITM systems distinct from that at Earth.

Implementation strategy: Deploy a high-resolution solar irradiance monitor to measure the spectrum of solar soft X-ray fluxes that are a primary source of photoelectrons and ions in the lower thermosphere.

Solar irradiance measurements are critical for continual improvement in the understanding of Earth's upper atmosphere, space weather, and fundamental solar physics. One of the most important strategic measurement gaps for ITM system science at Earth is a high-resolution solar irradiance monitor to measure the spectrum of solar soft D-ray fluxes that are a primary source of photoelectrons and ions in the lower thermosphere. Unless new measurements are planned for the next decade, there is a danger that there will be long gaps in these seminal measurements. The relative lack of measurements in the D-ray spectral region is of particular concern for its impact on Earth's lower thermosphere as well as the theory of solar flares. These soft D-ray irradiances can vary by more than a factor of 2 over a solar rotation and by an order of magnitude over a solar cycle. Inadequate knowledge of the D-ray spectra is a major reason why ionospheric models routinely underestimate the E-region peak electron density. Addressing this problem requires high-resolution measurements of the solar D-ray spectrum (~0.1 nm) and E-region photoelectron spectra (~5.0 eV).

D.6.5 Theory and Modeling

Theory and modeling are the elements that tie together basic research and observations. The advancement and breakthrough discoveries in ITM science can be achieved only through the careful coordination and integration of fundamental research, space- and ground-based observations, theory, and modeling. Empirical and assimilative models such as International Reference Ionosphere (IRI), Incoherent Scatter Radar Model (ISRIM), Horizontal Wind Model (HWM), and Mass Spectrometer Incoherent Scatter Radar (MSIS) are widely used by the community. "Whole atmosphere" physics-based models that extend from the surface to the thermosphere are being used in a number of ways: to investigate causality in attributing sources of ITM variability; to predict the future state of the ITM; and when used within data assimilation systems, to leverage observations to reduced model/data biases. Currently, owing to the complexity and resource-intensive nature of the models and data assimilation procedures, the running of these models is largely confined to institutions with large high-performance computing facilities. This situation is unlikely to change as the complexity and resolution of these models increases, unless there is a significant shift in how these models are implemented.

The four ITM PSGs for the next decade address the current knowledge gaps that relate to the coupling of the ITM system with regions above and below, and the coupling of physical processes within the ITM system, on a continuum of spatial and temporal scales. Achieving these PSGs requires ever-improving physics-based models that are two-way coupled and multiscale with vast dynamic ranges. This new generation of models needs to be subject to robust validation and have quantifiable errors and uncertainties. Some models need to be assimilative, with the capability to conduct OSSEs for optimal instrument design, deployment strategy, and operation of space missions.

Implementation strategy: Develop physics-based models of two-way coupling between physical domains, incorporating chemical–dynamical, plasma-neutral, horizontal, and vertical interactions.

The past decade has seen significant progress of physics-based models that treat Earth's atmosphere as an integrated system. For example, WAM-IPE and WACCM-X couple the ITM system with the lower atmosphere. WAM-IPE is also coupled to the plasmasphere and is the NOAA space weather forecast model. WACCM-X successfully simulated Lamb wave propagation from the epicenter of the Hunga Tonga volcanic eruption to the ITM, where it caused thermosphere temperature and wind oscillations and D-Shaped EIA crests that were observed by the GOLD satellite and ground-based TEC. The MAGE model being developed at NASA's DRIVE Center for Geospace Modeling couples the ITM system with the solar wind and magnetosphere. It simulated a much larger mass density enhancement than predicted by empirical models during the ionospheric storm that deorbited numerous SpaceX satellites. These modeling successes highlight the importance of external forcing in ITM modeling, demonstrating the need to continue to improve coupling processes in ITM modeling.

Implementation strategy: Further develop high-resolution model capabilities to enable investigations of ITM phenomena that are governed by coupling across temporal and spatial scales.

The coupled processes of the ITM system operate across a multitude of temporal and spatial scales. These couplings often happen at mesoscales and submesoscales, which are challenging to address from either the microphysics or global system point of view. Current limitations on computing power and adaptation of numerical techniques require the parameterization of some important physics such as gravity wave breaking. Overcoming these limitations requires the development of new modeling capabilities, including high-resolution, adaptive grid refinement, or nested-grid models to resolve these scales. In addition, it will be important to leverage the power of exascale supercomputing, machine learning, and artificial intelligence to create the first generation of cross-scale holistic geospace models.

Implementation strategy: Quantify model parameter uncertainties to support identification of key driver/response relationships in ITM physics.

Improving model fidelity demands a more rigorous level of error analysis, uncertainty quantification, and data assimilation. Structural uncertainty (i.e., uncertainty that stems from choices in how a model is assembled) has remained practically unquantified. Interoperability in model components and parameterizations (e.g., for subgrid scale waves, chemistry, and radiative transfer) would help with quantifying structural uncertainty and understanding model–model differences. Continued participation in model intercomparison projects (e.g., Coupled Model Intercomparison Project [CMIP], HEPPA), along with assessment of uncertainties stemming from poorly constrained laboratory measurements needs to be supported. Data assimilation can be utilized for model parameter estimation and identifying large systematic biases. Last, model accuracy depends critically on the quality of model inputs—to identify driver/response relationships, the driver uncertainty needs to be known.

Implementation strategy: Use Observing System Simulation Experiments (OSSEs) to facilitate optimal instrument design, deployment strategy, and operation.

Theory and modeling are integral parts of understanding ITM processes and variations in ways not possible with pure observational techniques, and OSSEs form an efficient productive tool to optimally implement these efforts. Ultimately, ideation and conceptualization of key ITM pathways frequently require physical intuition and interpretation from modeling. Furthermore, observation platform creation in the form of Phase A and instrument proposals, as well as science definition teams, often require both OSSEs with synthetic data and science development. OSSEs are also essential for the proper interpretation of mission observations.

Enhanced use of OSSEs in this manner will aid community development efforts, as theory and modeling are tightly intertwined through the need to develop techniques to effectively implement physics into numerical models. Improved theoretical calculations often must be developed before they can be adopted into models. To accomplish these goals, OSSEs will provide a practical and broad pathway to generate a new generation of theorists and modelers needed to perform the necessary and continued theory and model development, as these tools require diverse teams with expertise in disciplines across the ITM system.

D.6.6 Enabling Capabilities

Successful implementation of the strategies described in the current section rest on an underlying infrastructure of enabling capabilities. These include programmatic support for ITM strategic system science needs, efficient application of the new capabilities afforded by data science, key instrument development on strategically chosen timelines, advancement in access to space along multiple capability axes, laboratory investigations of key ITM parameters and pathways, and education and workforce development. This section details implementation strategies in these areas.

Programmatic Support

Implementation strategy: Prioritize the strategic needs of ITM system science through agency-level coordination of heterogeneous observation platforms, joint investigations of interacting physical processes, causality-focused studies, parameter uncertainty quantification, and career development of scientists who cross disciplines, niches, and boundaries.

The NSF, NASA, and NOAA agencies' structures, programs, funding mechanisms, and initiatives will be fundamental to fostering and enabling the full system science framework. The 2013 decadal survey and 2011 "CEDAR: The New Dimension" introduced and motivated a system science approach. Implementing system science at the highest levels will be the most streamlined and effective means of implementation. Agency structures and program lines are the "invisible hand" that tends by default to have the effect of siloing research into distinct disciplinary areas, so care needs to be taken so that agencies and proposal criteria do not reinforce unintended barriers and dichotomies (e.g., research versus operations, science versus application, space versus ground assets). The existence of these unintentional barriers stifles system-level creativity. Instead, balanced team formation and development of nontraditional success criteria are needed. Every programmatic support initiative mentioned in this subsection has the secondary effect of setting the priorities and capabilities for workforce development, through the opportunities afforded the next generation of researchers. While it is understood that it may not be feasible to implement all initiatives or program structures described in this subsection, the panel suggests that preference be given to continuing those programs that enable system science through focused teaming, data set continuity, and capability sustainment. Separate initiatives that target workforce development directly are discussed in the section "Education and Workforce" below.

Programs such as the NSF Convergence Accelerator and the NASA DRIVE Science Centers have moved in a system science direction and these programs can expand it further. NASA LWS Tools and Methods help encourage transdisciplinary teams, although the deliverables/closure requirements and duration are restrictive regarding the scope of the teams. Other areas of crossover that will result in potent benefits are (1) inclusion of fundamental plasma physics more completely within the purview of ITM area solicitations; (2) collaboration with lower atmosphere science to initiate contribution to climate assessments for the first time (e.g., Intergovernmental Panel on Climate Change [IPCC]); and (3) reinvigoration of the NASA ROSES B.3 Heliophysics Theory, Modeling and Simulation line to enable exascale computing for data-driven modeling and high-fidelity numerical simulation. Data buys from commercial constellations and programs requesting proposals for mass production of constellations can also help diversify data products and providers.

New mission lines and support for mission operations also will enable system science. NASA's GDC and DYNAMIC are already a welcome step in this direction, especially when coordinated with each other and with ground-based facilities for simultaneous observation. A new mission line to fill the gap between Medium-Class Explorers and flagship missions (i.e., fiscal year [FY] 2022 $500 million–$1 billion) would have the appropriate scale to address system science questions. Follow-on missions are needed to extend the current long-term data record, and a "geospace continuity" mission line would directly support PSG 4. To implement this concept, a study would be needed to identify and prioritize the quantities for which continuity is essential.

As stated throughout this report, long-term observational continuity and open availability of ITM state variables form an important linchpin in a future ITM strategy for effective system science focused work as well as support of ITM forecasting and space weather research. Achieving both measurement continuity and opportunities for focused studies in these areas can be effectively done by extending the hosted payload concept beyond commercial and other types of satellite platforms through utilizing high-heritage instruments on a combination of balloons, suborbital sounding rockets, and CubeSats. Additionally, it is important to maintain mission programs past original operation goals to extend targeted and calibrated observational data. Regardless of the strategy for maintaining or expanding long-term data set continuity, the inclusion of adequate support at the individual instrument and mission level is essential for processing, calibration, and preparation of data sets for open archives. This is particularly vital for existing research lines such as NASA's Heliophysics Low-Cost Access to Space (H-LCAS) and Heliophysics Flight Opportunities for Research and Technology (H-FORT) programs and NSF's Ideas Lab.

Interagency and international collaboration are also essential for ITM programs, as they enhance system science through bridge-building with partners and this creates the important potential to be cost-effective in a budget-constrained environment. An international solar-terrestrial probe next-generation (ISTPNext) program would connect small and large missions in this regard, as would the concept of an International Geospace Systems Program, which is being considered by the Committee on Space Research (COSPAR). Implementing an interagency coordination "office" has multiple benefits, as it can not only coordinate ground and space platforms for optimized system science yield, from design through operations timeframe but also coordinate theory and modeling initiatives focusing on causality and uncertainty quantification, and support fundamental ITM science that leads to, and supports, space weather research and operations in alignment with the PROSWIFT Act (P.L. 116-181).

Data Science

The toolset of the ITM scientist not only includes the apparatus for acquiring data and developing models but also crucially includes the digital tools for archiving the measurements and implementing the models along with the hardware and software frameworks for accessing the results for analysis and inference. The value of data science tools was recognized explicitly in the decadal midterm assessment report, *Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics: A Midterm Assessment* (NASEM 2020) that noted

> NASA and NSF should maximize the scientific return from large and complex data sets by supporting (1) training opportunities on modern statistical and computational techniques; (2) science platforms to store, retrieve, and process data using common standards; (3) funding opportunities for interdisciplinary collaboration; and (4) the development of open-source software. These four components should be considered alongside experimental hardware in the planning and budgeting of instrumentation.

While much progress has been made, more work still remains to be done. Progress is best achieved when implemented with sufficient resources, rather than an ad hoc or implicit approach.

Implementation strategy: Develop cohesive community tools and computational infrastructure that enables effective exploitation of heterogeneous ITM data products and models to facilitate system science.

Using tools effectively and creatively for ITM system science studies requires the infrastructure or "toolbox" for containing and organizing them. Ideally, a "digital lab bench" is needed to assemble them effectively. Achieving meaningful progress on each PSG for ITM therefore requires an effective hardware environment and software structures for containing, standardizing, and synthesizing these tools in a complete way. Such progress would benefit from continued discussions in community forums and workshops toward a planned, rather than ad hoc, strategy roadmap and implementation that maintains maximum scientific utility for ITM studies.

Implementation strategy: Establish and enforce community standards for open-access archiving and use of all ITM data and software products, with relevant documentation and parameter uncertainties in a common format.

Owing to its multiscale nature (PSG 2), ITM science uniquely benefits from the synthesis of heterogeneous data, and thus proper data archiving is imperative. More effective science is achieved with data products such as instrument measurements, model outputs, analysis software, and other products that are findable, accessible, interoperable, and reusable (FAIR). This makes such products readily accessible to the broadest possible community. Comprehensive access to past and current measurements is also directly beneficial for determining long-term persistent changes, which is the focus of PSG 4. Such science fundamentally requires continuous and easily accessible records, such as the ionosonde database, that go back to the dawn of the space age and beyond in some cases. Efforts in FAIR compatible systems and readily accessible long-term ITM product archiving need to continue and expand with dedicated resourcing.

Implementation strategy: Dedicate resources for coordinated public archiving of all ITM data and software products in support of ITM system science and open science research.

Continued and expanded support for the production of open science products is key. Unfunded mandates are unsustainable within the size of existing project awards. Defined support for the implementation of centralized frameworks for data containerization will relieve individual researchers of some of the burden of needing to create extraction tools and write software for each individual digital product. A number of such opportunities have been offered by agencies. Expanding or reimagining these at a level higher than the individual investigator (e.g., provision for dedicated ITM digital librarians) would be beneficial.

Access to Space

The coming decade will be marked by the rapidly growing opportunities available to the ITM community for global space-based observations. The decadal survey's Access to Space Working Group examined the various avenues of access that can be leveraged by both NASA and NOAA that are capable of supporting the agencies' strategic goals and advised the steering committee on options. In this section, those findings related to the ITM community are incorporated in addition to specific strategies agreed to by the ITM panel.

The number of small satellite launches in the past 5 years has increased by almost six-fold, with that number expected to continue in the coming years. A large portion of those launches will result from new commercially proliferated LEO constellations and launch vehicle development, which will enable new opportunities for hosted payloads. Combined with more balanced Explorers and Mission of Opportunity programs, these new opportunities are an important part of achieving the ITM system science priority goals.

Implementation strategy: Transform traditional instrument development, experiment planning, risk posture, and program support to leverage nontraditional commercial and suborbital hosted payload opportunities to enhance multipoint observations for ITM system science.

While commercial companies are open to hosting payloads, their interest is restricted to larger volumes (tens to hundreds) of instruments. Those companies providing the largest volume of sensors or buses will be driving the interfaces and subsequent standards. Careful consideration needs be paid to the companies developing interfaces as science instruments are developed. Furthermore, standards ought not be adopted for certain aspects (e.g., thermal, data volume) that overly restrict and limit the type of science instruments that can be utilized as hosted payloads.

Proliferated hosted payloads on commercial platforms and deployment of explorer constellations are exciting opportunities that can be utilized only if infrastructure and technological systems are modernized. Specifically, ground communication systems, data pipelines, and satellite operation systems need to be modernized. Furthermore, the miniaturization and improved reliability for various bus subsystems—such as radios, encryption, power generation, and attitude control systems—are needed if more sophisticated science instruments required for addressing the PSGs are to utilize the various access to space opportunities.

Current smaller-scale NASA space flight programs such as CubeSats, sounding rockets, and balloons are critical to the continued health of the ITM community for their ability to make scientific progress and train the next generation of PIs. These programs are valuable, but significant improvement in management, risk posture, and funding levels are needed over the next decade to ensure the programs' robustness. Continued support is needed for the long-standing suborbital sounding rocket and balloon programs, including experienced engineering and technical staff at flight facilities such as Wallops Island and Poker Flat. These avenues remain a crucial ITM observational tool for regions that can be reached only from these platforms. Separately, they also provide a workforce development line, with a long and successful heritage, in which a student can design, build, and fly an instrument; analyze data; and produce scientific results on a timeline consistent with graduate degrees. In addition, exploring partnerships with the international community to expand available launch locations strongly supports the priority system science goals of the ITM community.

While CubeSats have great potential for significant contributions, their implementation and success cannot follow traditional satellite missions' expectations. CubeSat missions offer many benefits for ITM science: unique science returns from lower budgets, multipoint measurements from constellations in place of a single large satellite program, a platform for technology demonstration, and training for next-generation engineering and scientific workforce. The NSF CubeSat program has demonstrated great success over the past decade in terms of technology demonstration, training, and public engagement and fills an important role for the health of the solar and space physics community. To realize CubeSat potential for heliophysics science at NASA, the panel suggests that the paradigm of increased risk acceptance (e.g., fly often and fail often) be embraced, along with the implementation of a significant funding increase ceiling per mission, prioritization of science return for metric of success, and deemphasis of the use of students for core engineering support (e.g., separate programs focused on training with lower science return expectations and higher risk tolerance). A high cadence of successful CubeSat missions with high science return expectations and the DEIA+[1] goal of promoting nontraditional flight institution participation may be incompatible with the current NASA CubeSat program funding and management approaches. Thus, the panel encourages continued discussions and innovations in the CubeSat program infrastructure and management, such as the creation of a CubeSat working group that incorporates lessons from established sounding rocket working group practices.

NASA's Science Mission Directorate (SMD) recently embraced as a standard practice the utilization of launches with excess mass capacity for secondary science payloads. Specifically, SMD stated that it would be adding Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter "ESPA ring" accommodations for additional payloads when excess capacity is available on flagship mission launches. One recent example is the call for secondary payloads for the NASA Heliophysics Interstellar Mapping and Acceleration Probe (IMAP) mission. The unique deployment opportunity to the Earth–Sun L1 Lagrange equilibrium point, enabled by rideshare with IMAP in 2025, has enabled implementation of the first dedicated exospheric mission, the Carruthers Geocorona Observatory.

Key Hardware Development

Acquiring the necessary and sufficient characterization of salient ITM state parameters to support system science investigations is a formidable task, owing to the wide diversity of upper atmospheric constituents, their energy and velocity distributions, and the fields in which they are embedded. While current ground- and space-based sensing capabilities are similarly formidable, several long-standing measurement gaps have precluded a complete understanding of fundamental processes that govern the structure and dynamics of the ITM system. Continued investment in new hardware development, including sensor miniaturization, bulk sensor fabrication modalities, maturation of TRLs, and novel measurement capabilities, is a vital part of a cohesive strategy to advance system science investigations of the ITM in the coming decade.

Implementation strategy: Continue support for novel ground- and space-based instrument development to enable measurements of key ITM state parameters.

One example of a key measurement gap, which was identified explicitly in the 2013 decadal survey, is neutral wind measurements over the altitude range from 90 km to 300 km, where the transition from a collision-dominated to a magnetized atmosphere occurs. The recent development of limb-scanning capability at terahertz frequencies has the potential to overcome the long-standing challenge of measuring thermospheric neutral wind profiles at night, and a TLS instrument plays a prominent role in both the BRAVO and I-Circuit mission concepts.

Height-resolved measurements of the vertical neutral wind in the MLT region are similarly recognized in this decade's ITM report as critical for understanding the role of gravity wave deposition in governing upper atmosphere dynamics, yet such measurements are also challenging to obtain. Investment in the TRL maturation of a space-based, nadir-viewing, LiDAR instrument, such as the linchpin sensor of the BRAVO mission concept, is required to ensure that this critical aspect of ITM system dynamics can be investigated in the coming years.

Ground-based LiDAR technology for sensing neutral winds above 400 km is another important observational area that has also been maturing over the past decade. Neither neutral winds nor neutral temperature near the ITM transition region from the collisional thermosphere to the collisionless exosphere have been measured in decades, despite the critical role that these state parameters play in governing atmospheric escape, interhemispheric neutral circulation, and field-aligned ion transport driven by charge exchange with exospheric hydrogen. Metastable helium atoms, which form a photochemically induced layer near 650 km, are a particularly attractive target for LiDAR fluorescence, and further maturation of near-infrared helium LiDAR technology would offer an important new capability for a future LiDAR facility as described in Section D.6.3, "Ground-Based Facilities."

Another long-standing ITM measurement gap is cold (total energy less than ~100 eV) particle populations. While they often account for a large portion of the total density, measurements of these populations are limited owing to spacecraft charging (for ions) and photoelectrons and secondary electrons overwhelming the signal (for electrons). New instrument development is needed to enable measurements of these particles to improve understanding of outflow, the polar wind, and the filling and emptying of the plasmasphere.

[1] See the discussion in Chapter 4 on DEIA+ (diversity, equity, inclusion, and accessibility, as well as anti-racism, accountability, and justice).

Last, routine and global observations of neutral atmospheric parameters (winds, temperatures, composition, and density) at 100–300 km altitudes are critical for progress on nearly all subobjectives of the PSGs. In particular, development of mass spectrometers that can distinguish composition between N^+ and O^+ ions is needed to improve understanding of the role of nitrogen atoms in outflow and ion-neutral interactions, while those that can distinguish between light neutrals are needed to improve understanding of upper thermospheric composition and its role in atmospheric escape and plasmaspheric dynamics. The past decade has seen much effort to mature and miniaturize ion-neutral mass spectrometers (e.g., Ion and Neutral Mass Spectrometer [INMS], Winds-Ion-Neutral-Composition Suite [WINCS]), but further investment would ensure the success of this vital direct sensing capability that overcomes the limitations of traditional optical remote sensing.

Implementation strategy: Support the transition of current single ITM sensors' development to multiple sensor (<25) build processes to take advantage of expanding hosted payload and distributed network deployment opportunities.

The ongoing reduction in in situ sensor mass, power, and size in the past decade motivates investment in new approaches for multiple ITM sensor fabrication. Such efforts, which include the careful assessment and implementation of appropriate interfaces, create an important step toward improving the spatial coverage and resolution of key ITM state parameter measurements that are a vital component of comprehensive ITM system science investigations.

Laboratory Experiments

Implementation strategy: Enhance support to stimulate laboratory measurements of key physical parameters and processes that will reduce uncertainty in physics-based models and derived data products.

While direct measurements within the ITM system provide vitally important data for testing the physical understanding of system processes, it remains a challenge to determine which parameters govern observed phenomena. Controlled laboratory experiments are a necessary pathway to reduce model uncertainties and improve the fidelity of OSSE results.

An improved database of atomic and molecular measurements is needed to reduce uncertainties in models that incorporate radiative transfer. Currently, there are multiple databases with information relying on varying assumptions that are not always clear. Collaboration with atomic/molecular physicists along with support for a centralized database is needed to include critical measurements along with the background assumptions so that they can be accurately incorporated into models. Critical measurements include atomic data, transition rates, charge exchange, cross sections, and photoionization and recombination processes.

There is an urgent need to resolve major uncertainties in energetic electron flux calculations by making direct laboratory measurements of the total inelastic electron impact cross sections and the total excitation cross sections for O and N_2. Energetic electron fluxes are important for calculating ionization rates and the many emissions that are used for remote monitoring of geospace.

The largest cross sections in Figure D-25 were obtained by summing available laboratory partial cross-section measurements, which can lead to double counting. The FLIP model uses laboratory cross sections that are selected to reproduce the Atmospheric Explorer-E (AE-E) and FAST satellite measured ionospheric photoelectron fluxes. The differences in cross sections can lead to a factor of 2 difference between the model electron fluxes.

To improve the accuracy of neutral mass densities in the thermosphere (PSG 3), a better understanding of gas–surface interactions (GSIs) would reduce the uncertainty in the drag coefficients that are used. This requires laboratory experiments of beam scattering combined with comparative measurements between satellites orbiting in close proximity with different attitude states (e.g., GDC and Space Weather Atmospheric Reconfigurable Multiscale Experiment [SWARM-EX]) and during various levels of geomagnetic activity to improve model validation.

Education and Workforce

Implementation strategy: Enhance support of ITM educational programs to acquaint and attract students, maintain continuity across ITM researchers from disparate fields, develop programs to sustain intergenerational expertise on critical ITM techniques, and provide resources for supporting workforce vibrancy at all career stages.

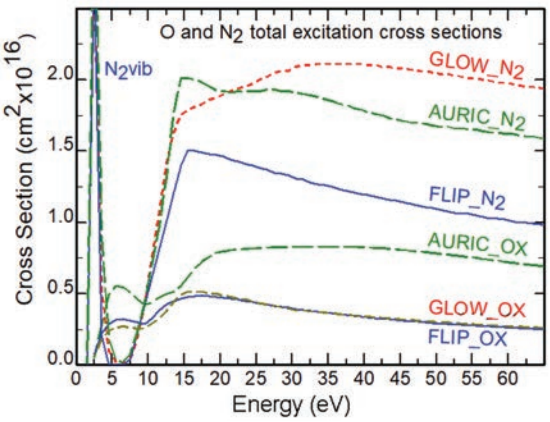


FIGURE D-25 O and N_2 total excitation cross sections used in the well-known GLobal airglOW Model (GLOW), Atmospheric Ultraviolet Radiance Integrated Code (AURIC), and field line interhemispheric plasma (FLIP) energetic electron models.

ITM science is inherently interdisciplinary, which underpins the effectiveness of treating it as a system of systems. ITM researchers need to draw from a wide range of physical science, engineering, and computer science fields, which are often siloed in different departments at different educational institutions. Properly preparing ITM researchers for long and successful careers requires reducing the siloing of their training to develop a generation of scientists with the skills to nimbly cross disciplines, niches, and boundaries to effectively meet exciting ITM science challenges. Continued educational programs, inspiring students with ITM science, will help cohere and maintain continuity in ITM research spanning disparate fields. In-person, virtual, and hybrid summer schools, workshops, and training opportunities are needed for the broadest possible community, including DEI and international partners.

With the retirement of the Apollo generation, who were inspired as children and went on to become ITM scientists and engineers, key expertise in ITM experimental remote sensing methods such as IS radar and sounding rocket experiments is now at risk of being lost without adequate training support. Many of these complex techniques would be challenging to "cold restart" using only the published literature. Existing programs such as the NSF Faculty Development in Space Sciences and Faculty Early Career Development (CAREER) are aimed at providing faculty support to sustain and grow the next generation of researchers. However, these programs are not currently implemented as a strategic approach aimed at needed training in ITM experimental areas.

The panel asserts that maintaining expertise and facilitating knowledge transfer in critical observational techniques is a necessary core foundation for progress in ITM science, and it will help the United States maintain its scientific leadership. The development of dedicated support for establishing faculty lines at universities and government institutions to coordinate transdisciplinary work will help cross-pollinate and de-silo the span of heliophysics activities. Embracing the system-of-systems perspective means that graduate training will need to include numerical methods, statistics, and data science, as well as the ability to conduct "cross-over" transdisciplinary activities.

To maintain a robust ITM workforce, there is a need to provide continuity of support at all career stages. This involves expanding technical and science project opportunities, including careers involving interdisciplinary work to maintain a healthy range of ITM community member expertise. In particular, the GDC and DYNAMIC missions will contribute to these aims when jointly supported by well-coordinated ground instrumentation and software infrastructure. Beyond these projects, properly resourced new missions and ground-based facilities offer opportunities to cohere, maintain, and grow the ITM science community for the future ITM workforce.

Maximizing retention in the field and supporting a vibrant research community requires career and educational resources that improve mental health and create a positive learning environment. These types of resources, along with improved funding, will enable all researchers to focus on science, data archiving, and communicating the exciting achievements of the future.

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E

Report of the Panel on Space Weather Science and Applications

The scope of the report from the Panel on Space Weather Science and Applications (SWSA) includes the following:

1. An overview of the current state of research and operational capabilities related to space weather.
2. Identification of the highest-priority research and operational goals and investments to address space weather user needs and enhance the space weather pipeline from basic research to applications to operations for 2024–2033.
3. A strategy to address the research and operational goals.
4. Identification of investments needed to lay the groundwork for continued advancement in future decades.

Addressing these topics resulted in a large number of "goals," which have been divided here into three categories: basic research, applied research, and operational needs. It also led to a panel report that is significantly longer than those of the other survey study panels.

With its connection to day-to-day forecasts of potentially hazardous space weather, a delay in the achievement of the goals of the SWSA panel poses societal costs. In contrast, similar delays in the achievement of the goals of the decadal survey's science discipline panels may be less consequential. Thus, the SWSA report includes goals whose achievement will ensure that agencies can make informed and timely decisions regarding space weather and societal impacts, as well as goals to advance understanding of the science that underlies space weather phenomena. *These goals have different significance depending on the end user; therefore, in this report, they are not presented in priority order.*

This report begins with an introduction that highlights the rapid increase in the importance of space weather; working definitions of the key terms used in this report follow. A brief summary of space weather activities under way at the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Department of Defense (DoD), and their international partners, are then presented to provide background to the discussion of the panel's priority goals for the survey interval, strategies to achieve these goals, and longer-term goals and emerging opportunities.

The panel's report also includes annexes covering the organizational development of the space weather enterprise (Annex E.A), space weather utility assessments of specific mission concepts provided by the steering committee (Annex E.B), and assessments of ground-based contributions to space weather (Annex E.C). However, given the

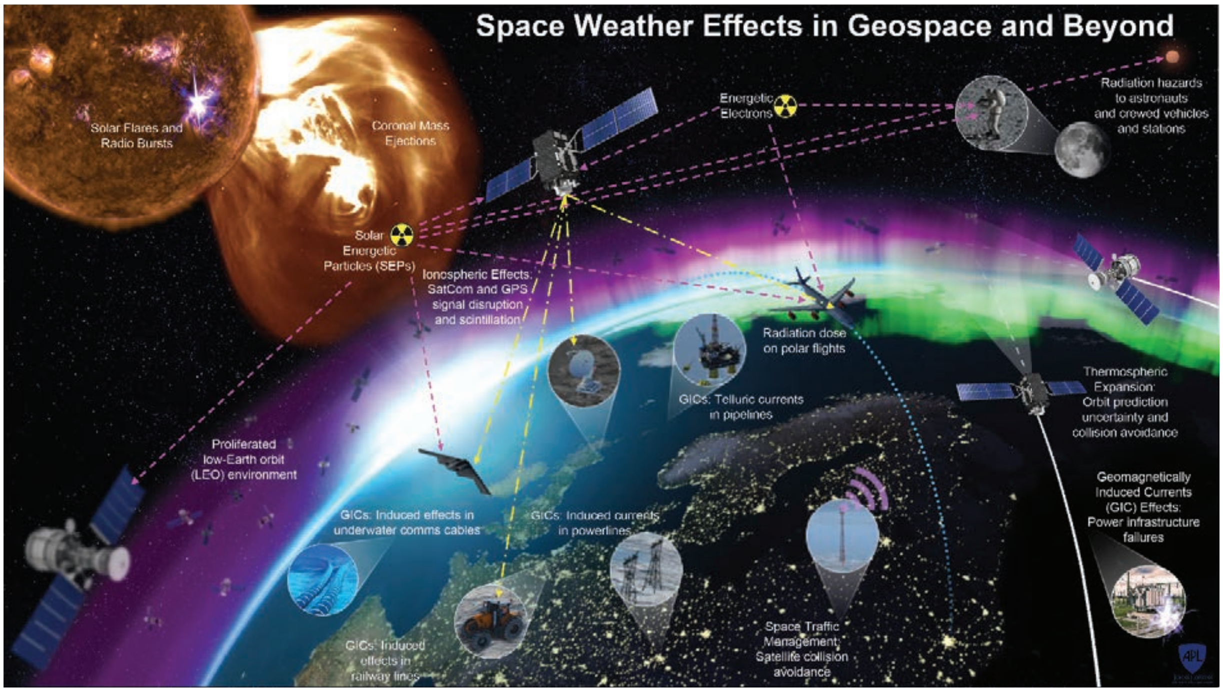

FIGURE E-1 Space weather effects in geospace and beyond.
SOURCE: NASA (2021), compiled by APL.

length of the SWSA report, the complete text of Annexes E.A, E.B, and E.C are available only in the online version of the decadal survey report. Last, the panel notes that while it makes *suggestions* for actions in this appendix, the authority to make final consensus recommendations, conclusions, or findings rests with the steering committee.

E.1 INTRODUCTION

E.1.1 Expanding Importance of Space Weather

Except for climate change, space weather may be the fastest-growing geophysical hazard to society. Every currently operating spacecraft—and the many more that will be launched in the future[1]—is subject to the constant variability and sporadic episodic nature of space weather. Understanding the physical causes of space weather, or at least characterizing the causes and impacts of space weather, is essential for the entire spaced-based economy, including mission and payload design, management of space traffic, developing mitigation response and recovery for space-based assets (e.g., communications satellites) and ground-based infrastructure (e.g., the power grid), safely exploring the heliosphere and solar system, and much more (Figure E-1). Space weather science and its applications are a necessary part of a foundation to enable NASA to achieve its vision of "exploring the secrets of the universe for the benefit of all."

In the past 21 years, the Sun has had only mild and moderate levels of solar activity (Figure E-2). During this time, society's reliance on technology sensitive to space weather—for example, GPS—has increased dramatically, with effects across a multitude of economic sectors, including defense, aviation, the power industry, emergency services, and the commercial space flight industry. However, the comparatively benign space weather environment

[1] In the spring of 2022, the number of active satellites was estimated to be almost 5,500. By 2030, that number was predicted to rise by an additional 58,000. See GAO (2022).

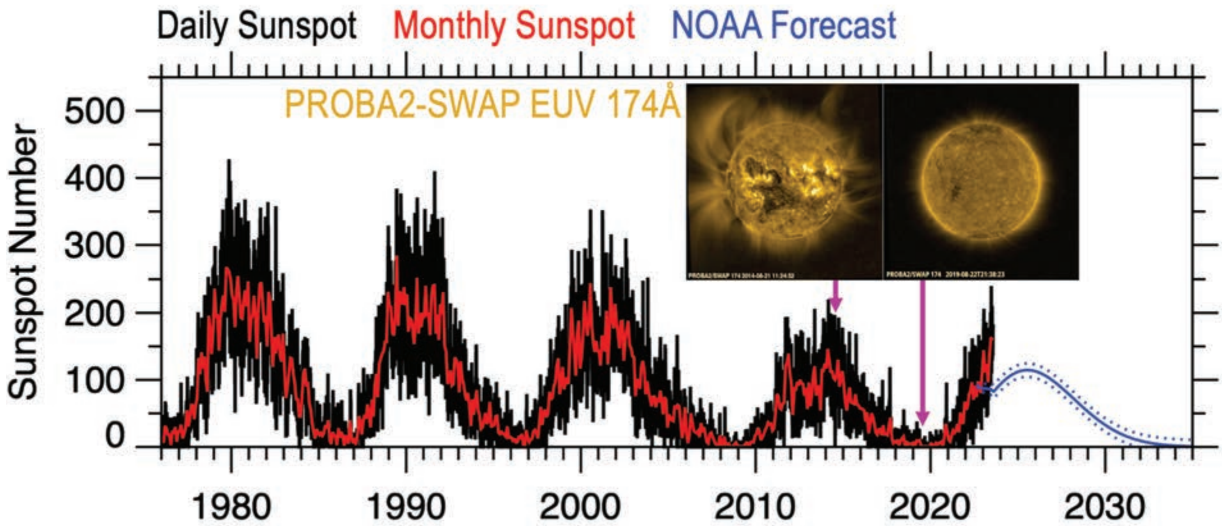

FIGURE E-2 Our reliance on technology sensitive to space weather increased when the solar activity was low, but now the activity level is increasing.
SOURCES: Sunspot number data from WDC-SILSO, Royal Observatory of Belgium, Brussels; Forecast sunspot number from NOAA/SWPC; EUV 174 images from West et al. (2022), https://doi.org/10.1007/S11207-022-02063-9. CC BY.

of the recent past may be changing. In October 2023, NOAA's Space Weather Prediction Center (SWPC) issued a revised prediction for solar activity during Solar Cycle 25, concluding that solar activity will increase more quickly and peak at a higher level than that predicted by an expert panel in December 2019.[2]

In a 2019 event hosted by the U.S. Chamber of Commerce and the SmallSat Alliance, keynote speaker Ajit Pai, then chair of the Federal Communications Commission (FCC), highlighted the importance of the space sector by stating, "Whether they know it or not, all companies will be space companies" (NSS 2019). Pai's statement is notable given that global market sectors are shifting to rely heavily on technologies and services affected by space weather. The global space industry generated approximately $424 billion in economic activity in 2020, up 70 percent from 10 years earlier, and is projected to surpass $1 trillion by 2030 (Figure E-3). According to the U.S. Bureau of Economic Analysis (BEA), in 2021 the U.S. space economy had $211.6 billion of gross output and consisted of $129.9 billion or 0.6 percent of gross domestic product (GDP), implying that the U.S. space economy is about half of the global space economy. Additionally, the U.S. private space industry compensation was $51.1 billion with 360,000 private industry jobs.

Eventually, more debris will be created from these additional spacecraft unless timely reentry or transfer to a graveyard orbit can be ensured for each spacecraft. Therefore, now more than ever there is an increasing need to understand the risks, mitigations, and design environment, and a need to leverage future economic opportunities associated with the space environment. In the March 2023 *NASA Cost and Benefit Analysis of Orbital Debris Remediation* report (Colvin et al. 2023), the growing need for debris remediation is acknowledged and several methods of remediation are examined.

The government has been responding to the growing space weather needs through a wide variety of actions and organizational changes. Some examples are the formation of the Space Operations, Research, and Mitigation (SWORM) interagency working group designed to coordinate space weather activities, the Space Weather Advisory Group (SWAG), which is tasked to survey space weather end users and researchers and advise the SWORM on strategic priorities, and the National Academies of Sciences, Engineering, and Medicine's Government-University-Commercial Roundtable on Space Weather to facilitate communication and knowledge transfer among Government

[2] The 2019 panel, convened by NOAA, NASA, and the International Space Environment Services (ISES), produced the forecast. See NOAA Space Weather Prediction Center (2024).

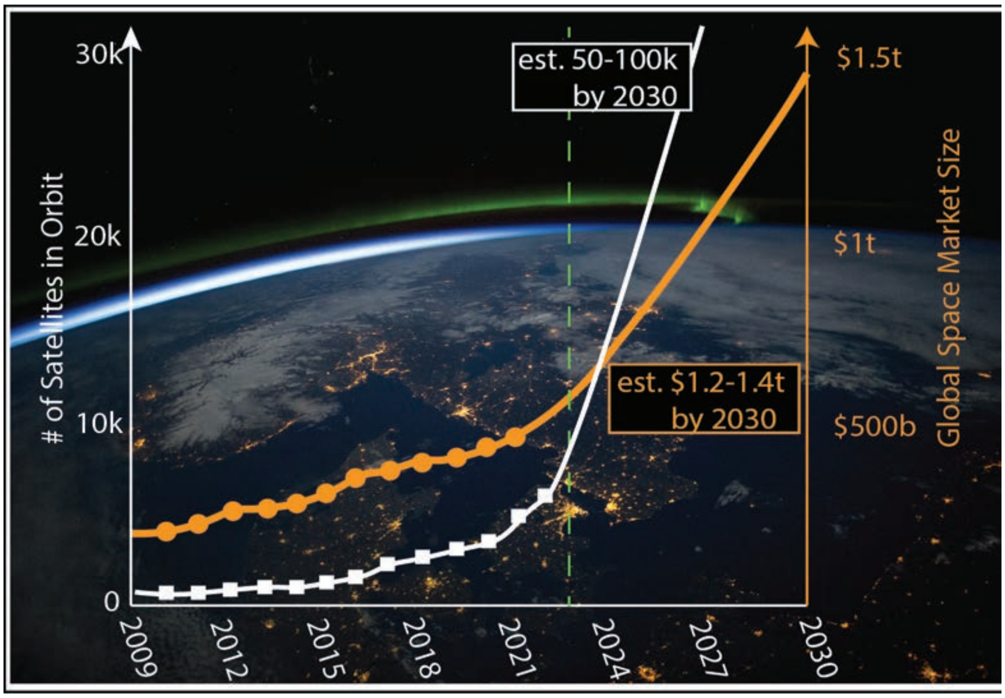

FIGURE E-3 Time series of the number of satellites in orbit (white) and time series of the size of the global space market size in dollars starting in 2009 and extrapolated to 2030.
SOURCES: Adapted from Space Foundation/The Space Report. Background image from NASA Visible Earth.

participants in the SWORM Interagency Working Group, the academic community, and the commercial space weather sector. Space weather roles for specific branches of the government were clarified in the PROSWIFT Act;[3] these have been supplemented by interagency memorandums of understanding and agreement (MOUs and MoAs).[4] Also of note are the completion of space weather strategy and action plans (Weather.gov 2023; White House 2023), development of space weather benchmarks (NSTC 2018), the release of the NASA Moon-to-Mars (M2M) architecture plan (NASA 2023), and the publication of a comprehensive Space Weather Gap Analysis (NASA 2021). Roles and plans for the various agencies to address the urgent Space Traffic and Space Situational Awareness have also been established. Additional details with references to specific space weather agency documents, congressional acts, and executive branch orders and policies can be found in Annex E.A.

E.1.2 Definition of Terms

The term "space weather" refers to the physical state of the space environment and the solar and nonsolar phenomena that disturb it, but the term can also refer, somewhat ambiguously, to a domain within space science (Lilensten and Belehaki 2009; Morley 2020). Most often, space weather is practically understood as an applied science with a primary focus on its impact on human systems and technology near and on Earth (NASEM 2022),

[3] In October 2020, Congress passed the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT Act; P.L. 116-181; 51 USC §§60601–60608). See https://www.congress.gov/bill/116th-congress/senate-bill/881.

[4] Most recently, SolarNews, 2023, "QUAD Agency Memorandum of Understanding for R2O2R Signed," December 14, https://solarnews.nso.edu/quad-agency-memorandum-of-understanding-for-r2o2r-signed.

although as human exploration expands, space weather at other locations of interest in the solar system (e.g., Mars) is rising in importance.

To prepare this report, the panel needed to have working definitions of two key terms: *space weather science* and *space weather operations*. The study of space weather and the steps needed to achieve a particular application required by end users (e.g., a forecast) have substantial overlap with the work done in the general field of space physics/heliophysics. While nowcasting and forecasting space weather is the purview of NOAA (NASA coordinates with NOAA as needed for exploration and off the Sun–Earth line mission support), space weather research is supported by multiple agencies, including NOAA, NASA, NSF, and DoD, as well as academia and the commercial sector.[5]

Separating space weather science from space physics/heliophysics is generally not simple, nor is the division completely agreed upon. The word "research" is itself used rather broadly to encompass a range of activities from fundamental to applied scientific research. The panel's guidance for categorizing research activities is primarily driven by the motivation behind the work. While the majority of fundamental research for space science and space weather science may be the same, the incentives are typically different. Fundamental space science research can be driven purely by the desire to discover new phenomena and/or better understand the natural space environment, regardless of whether it may have an ultimate application to space weather. In contrast, space weather research is driven primarily by the need to improve the ability to characterize and predict the space environment with an end user application in mind.

In practice, for space weather science there ought to be a reasonably clear, straightforward pathway connecting the science to a specific potential end product or end user need. A good example of the dividing line between space science and space weather science research is seen by comparing the definitions of NOAA's RL 1 (Readiness Level 1) and RL 2 (Figure E-4), with RL 1 being basic space science research and RL 2 being space weather science (NSTC [SWORM] 2022).

The term "space weather operations," in analogy with tropospheric weather operations, refers to the activities and assets used to monitor, nowcast, and forecast the space environment phenomena that impact human activities and the impacts themselves. There is also a sub-branch of space weather operations that engages in emergency forensic analysis of satellite failures for the purpose of attributing failures to natural causes, component or system failure, or adversarial attack.

For many, especially in the forecasting community, the term "operations" implies continuous—24/7/365—fail-safe, real-time or near-real-time, data acquisition and analysis to create a time-critical product (e.g., a forecast or nowcast) that is used to inform actionable end user decisions. Others, especially consumers of space weather information, have a broader definition of space weather "operations" that includes data or products or applications that are used for long-term planning, mission design, anomaly attribution and forensic assessment, or mitigation strategies and best practices (e.g., "climatological" products and benchmarks). Furthermore, there are activities relating to the transition of scientific knowledge and understanding gained from space weather research to applications/tools, as well as the reverse with tool needs informing space weather research. While these non-time-critical activities may not in the strictest sense be clearly "operations," neither are they fundamental space science research. They can be combined with operations into the larger term "space weather applications."

In this report, the panel adopts the following working definitions:

- *Space weather science* involves systematic studies to gain the knowledge or understanding necessary to determine how a recognized and specific application for space weather operations and/or end users may be met. In other words, space weather science involves applied research directed primarily toward a specific, practical aim or objective relevant to space weather operations and end user needs. The research is undertaken either to determine possible practical applications for the findings of basic research or to determine new methods or ways of achieving specific and predetermined objectives. Space weather science falls largely in RL2 in the NOAA framework.

[5] This paragraph was modified after release of the report to accurately reflect space weather nowcasting and forecasting responsibilities.

FIGURE E-4 The Space Weather Research to Operations "funnel." The funnel represents the process of distilling a large body of space physics/heliophysics research into a relatively small set of models, observations, and products used in real-time forecasting, nowcasting, and forensic analysis. Gray arrows indicate the directional flows of Research-to-Operations (R2O) and the critical feedback process of Operations-to-Research (O2R) that informs the research community of the effectiveness of current products and the requirements for essential new capabilities. Readiness levels (RLs) for operations-bound technologies are indicated on the scale on the right. Horizontal dashed lines indicate major transition steps, with RL 1–4 generally considered "research and development," RL 5–6 encompassing testing and validation steps, and RL 7–9 indicating final demonstration, refinement, and transition to operational offices.
SOURCE: NOAA/SWPC, 2022, "Space Weather Prediction Testbed: R2O2R Overview," https://testbed.swpc.noaa.gov/r2o2r/r2o2r-overview.

- *Space weather applications* is a term that includes space weather operations, benchmarking, and climatological activities and work relating to the bidirectional connection between space weather science research and space weather tools. Specifically, space weather applications cater to all the needs and requirements of the space weather end user communities. Space weather applications fall largely in the RL3 to RL6 range in the NOAA framework.
- *Space weather operations* are a subset of applications, consisting of the activities and assets used to monitor, nowcast, forecast, and forensically reconstruct the space environment phenomena that impact operational systems (both human and technological) and activities and the impacts themselves. Operations are usually characterized by 24/7/365 staffing, real-time data streams, and fail-safe systems. Space weather operations fall largely in the RL7 to RL9 range in the NOAA framework.

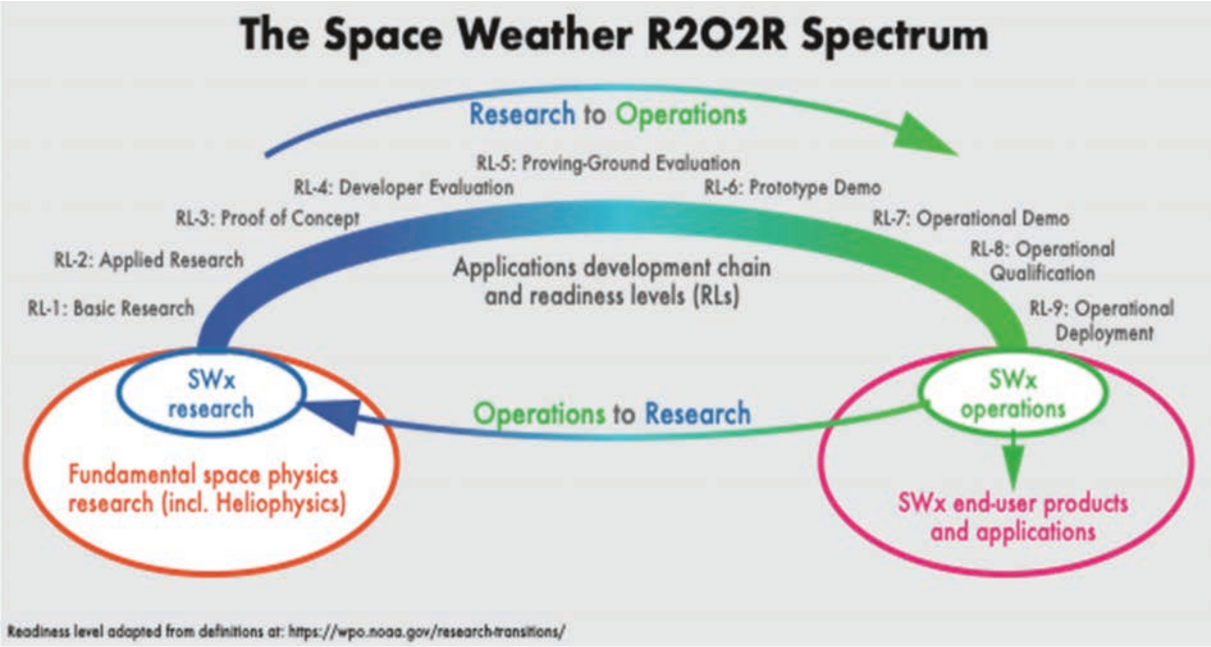

FIGURE E-5 Flow diagram highlighting how space weather (also sometimes abbreviated SWx) encompasses a continuous spectrum spanning basic research to operations, end user products, and applications. On the research side, space weather research is an applied science subset of fundamental space physics, and to truly qualify as space weather research, studies and projects need to identify a clear pathway along the spectrum to operational and applicational product development that satisfies some end user needs and requirements. On the operations side, space weather operations represent only one specific subset of space weather end user products and applications; other examples of end user products and applications include engineering design tools, benchmarking, reanalysis and climatological models, and forensics work. As also illustrated, the R2O2R spectrum is inherently a feedback loop, involving not only development from basic research to new operational and applicational products required by end users, but also critical information about vulnerabilities and end user needs and requirements flowing back from the operational and end user communities to the space weather research community.
SOURCE: NOAA Weather Program Office, 2024, "Research Transitions," https://wpo.noaa.gov/research-transitions.

Figure E-5 illustrates the connections between research and operations, in terms of an R2O2R spectrum. Note that with the introduction of the broader category of space weather applications, the panel suggests that R2O and O2R can be likewise thought of more broadly as R2A (research to applications) and A2R (applications to research).

E.2 STATE OF SPACE WEATHER

E.2.1 Recent Progress by the Space Weather Enterprise

The previous decadal survey was published in 2013 (NRC 2013; hereafter the "2013 decadal survey"). Since then, government agencies have made significant efforts to keep pace with the growing space economy and implement strategies to understand and mitigate the impact of space weather. In this section, the panel highlights recent accomplishments by the agencies and progress in achieving international collaborations.

National Oceanic and Atmospheric Administration

In the past decade, NOAA has made notable progress toward enhancing its space weather products and services. The NOAA SWPC has brought online new and updated space weather models, including the University of Michigan's Space Weather Modeling Framework (SWMF) Geospace Model, the U.S.–Canada Geoelectric Field models, the Federal Aviation Administration (FAA) Civil Aviation Research Institute-7 (FAA CARI-7) aviation radiation model, and NOAA/CU-CIRES (University of Colorado–Cooperative Institute for Research in Environmental Sciences) Whole Atmosphere Model–Ionosphere Plasmasphere Electrodynamics (WAM-IPE) coupled with the Global Forecast System (GFS) lower-atmosphere weather model.[6] NOAA SWPC has also led an international effort to upgrade the space weather scales that reflect advancements in usage, impacts, and regional differences.[7] To further accelerate the transition of research capabilities into operations, NOAA is establishing the Space Weather Prediction Testbed (SWPT; see NOAA SWPC 2022) to evaluate forecast tools and models and to bring together researchers, forecasters, and end users.

The 2020 Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT 2020) requires NOAA to sustain baseline space weather observing capabilities. As part of its response, NOAA reorganized its L1, GEO, and LEO space weather observing programs under a new National Environmental Satellite, Data, and Information Service (NESDIS) Office of Space Weather Observations (SWO) that is tasked with developing and deploying operational satellite systems for space weather monitoring. In 2025, NOAA will deploy the Space Weather Follow-On at L1 (SWFO-L1). SWFO-L1 will be launched as a rideshare with NASA's Interstellar Mapping and Acceleration Probe (IMAP) mission, currently scheduled for launch in the second half of 2025. It will be equipped with solar wind plasma and magnetic field instruments to sustain in situ monitoring of the solar wind upstream of Earth, and with an operational coronagraph to remotely track coronal mass ejections (CMEs). An operational coronagraph is also included on NOAA's Geostationary Operational Environmental Satellite-19 satellite (GOES-19), which launched in June 2024.

In the ionosphere–thermosphere–mesosphere (ITM) area, NOAA and the DoD/Air Force partnered with Taiwan's National Space Organization (NSPO), University Corporation for Atmospheric Research (UCAR), NASA-JPL, and others to execute the Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC-2) program. The COSMIC-2 satellites include a Tri-Global Navigation Satellite System (GNSS) Radio-Occultation System (TGRS) for measuring ionospheric scintillation and atmospheric profiles, Ion Velocity Meter (IVM), and Radio Frequency Beacon (RFB). In addition, in 2022, NOAA awarded three Commercial Weather Data Pilot (CWDP) space weather contracts to commercial providers to provide near-real-time radio occultation (RO) measurements from GNSS receivers, and to evaluate of the quality and impact of that data on ionospheric forecast models. In fiscal year (FY) 2016, NOAA also began contributing approximately $1 million for the annual operations and maintenance of the ground-based Global Oscillation Network Group (GONG) solar observing network, which is operated by NSF for space weather monitoring.

The Abt Associates 2019 report *Customer Needs and Requirements for Space Weather Products and Services* report (Abt Associates 2019), conducted for NOAA, highlights user needs for the electrical power industry, satellite operators (see also Green et al. 2017), GNSS users, aviation, and emergency managers. Some common themes were the need for All Clear forecast (times of low activity), accessibility and usability of data and products, improved lead time, precision and granularity of data and forecasts, the availability of historical data products and forecasts, improved granularity of activity scales and geomagnetic indices, and education and outreach for both end users and researchers.

National Aeronautics and Space Administration

Since the 2013 decadal survey, NASA's Heliophysics System Observatory (HSO) has increased to 19 operating missions with 13 more in various stages of development, all driving the fundamental research that is required for a better understanding of the Sun–Earth system. In response to the PROSWIFT Act, NASA established a Space Weather Program within the Heliophysics Division and recently selected the Space Weather Centers of Excellence (COEs) (NASA 2023). In collaboration with NOAA, NSF, and the DoD, NASA also established the Space Weather Research to Operations to Research (R2O2R) program to accelerate the transition of research to operations.

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[6] See "Products and Data," NOAA-NWS Space Weather Prediction Center, https://www.swpc.noaa.gov/products-and-data.
[7] This paragraph was modified after release of the report to accurately reflect NOAA's international efforts.

The ongoing Artemis lunar missions and future plans for crewed missions to Mars represent a major focus for NASA (2024), and with it, a renewed requirement for space weather forecasting support. A key element of the Artemis program is *Gateway*, a small lunar space station that is being built in collaboration with international and commercial partners. Gateway is a vital component of the human return to the Moon and a step forward on the path to Mars. Orbiting the Moon, it will provide essential support for lunar surface activities, a strategic post for scientific research, and a platform to prepare for deep exploration. Many instrument packages are being designed for the Gateway, including the Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES), a space weather payload that will make measurements of the solar wind and Earth's magnetotail from the polar lunar orbit of the Gateway Habitat and Logistics Outpost (HALO) module. HERMES is being designed to support deep-space and long-term human exploration (Brown 2022).

NASA and NOAA are working together to meet the emerging needs for Moon and Mars exploration. An interagency agreement was signed with NOAA SWPC for continued space weather support of the International Space Station (ISS), lunar Artemis, and Mars programs. In 2018, the Integrated Solar Energetic Particle Warning System (ISEP) project was established as a collaboration between NASA Community Coordinated Modeling Center (CCMC) and the Space Radiation Analysis Group (SRAG) to transition solar energetic particle (SEP) research models into operations. To meet the operational needs of the Artemis program, NASA developed and validated SEP models and forecast tools tailored for SRAG needs. This effort required real-time radiation monitoring and validation during critical mission operations which led to the development of the Moon to Mars (M2M) Space Weather Analysis Office. All human-in-the-loop space weather analysis capabilities for NASA robotic missions were also transitioned to the M2M Space Weather Analysis Office. The M2M office provides "proving ground" support for new capabilities before they are transitioned to operational agency testbeds.

In 2021, NASA, under a task order to the Johns Hopkins University Applied Physics Laboratory, commissioned a space weather science and measurement gap analysis that was performed by a committee of experts from academia, the commercial sector, and the space weather operational and end user community. The report from this analysis, published in April 2021(NASA 2021), assessed NASA's ability to address the science of space weather and the ability to provide the data needed to advance forecasting and nowcasting capabilities. It also identified high-priority observations that are at risk, or are not currently available, but are needed to significantly advance forecasting and nowcasting capabilities—themes reflected in the priority goals identified in this panel report.

Although orbital debris is not historically within the scope of space weather, NASA has recently recognized the association, given that orbital debris is a technological problem and is heavily influenced by thermospheric drag at low altitudes. Orbital debris, especially small debris that cannot easily be tracked, is expected to be a growing concern as ever more satellites are deployed into low Earth orbit (LEO). Through efforts of NASA and other agencies, space weather is expected to play an important role in understanding, monitoring, and mitigating this hazard.

National Science Foundation

NSF has continued to support ground-based space weather measurements, including the GONG solar observing network, ground-based magnetometers, ionosondes, and the neutron monitor network; it also supports fundamental space weather science via the newly created Space Weather Program (SWP) in the Atmospheric and Geospace Sciences (AGS) Division. In 2021, the SWP developed the Advancing National Space Weather Expertise and Research toward Societal Resilience (ANSWERS) and Next Generation Software for Data-Driven Models of Space Weather with Quantified Uncertainties (SWQU) funding opportunities. NSF continues to play a critical role in space weather education and workforce training by funding students to attend the annual Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR); Geospace Environment Modeling (GEM); and Solar, Heliospheric, and Interplanetary Environment (SHINE) workshops; the operation of the Boulder Space Weather Summer School; and unsolicited proposals for projects that support students and postdoctoral research. The agency also funds students to attend the annual Space Weather Workshop that it cosponsors with NOAA and NASA.

Space Traffic and Space Situational Awareness Across Agencies

A major development in the past decade has been the rapid increase of satellite launches—in particular, to LEO—with plans for megaconstellations consisting of tens of thousands of satellites well under way. The U.S. government is responding to the increased need for SSA, releasing Space Policy Directive 3 (SPD-3) National Space Traffic Management Policy in 2018 (White House 2018), which mandated that a civilian agency assume all space traffic management responsibilities for civil satellite operations, allowing the U.S. Air Force (later, the U.S. Space Force [USSF]) to manage only military assets. This responsibility was assigned to NOAA's Office of Space Commerce (OSC), originally a program in the NESDIS line office, but now chartered under NOAA HQ.

In 2022, OSC initiated a pilot program to provide spaceflight safety mission assurance to select spacecraft in the medium Earth orbit (MEO) and geostationary Earth orbit (GEO), through a partnership with DoD (NOAA 2022). Extending on the current space traffic management capabilities of the USSF, the OSC is developing the Traffic Coordination System for Space (TraCSS) to provide satellite tracking data and associated conjunction warning products for civil space satellite owner/operators in all orbits. It will be critical to incorporate operational space weather data and models into TraCSS. In particular, a civil version of a data-assimilative thermospheric density model along with associated analysis tools, analogous to the HASDM model currently used by the USSF for space traffic management, must be developed to ensure successful conjunction analysis in the increasingly congested LEO orbital regime.

Defense

Given the sensitive nature of the DoD needs, work, and plans, a comprehensive review is beyond the scope of this report. Other venues, such as the SWORM, provide opportunities for agencies covered by this report to collaborate with DoD to address common needs. DoD has provided some information about its activities to the public—for example, at the National Academies' Space Weather Operations and Research Infrastructure Workshops[8] and at the 2021 Advanced Maui Optical and Space Surveillance Technologies (AMOS) conference (Andorka et al. n.d.). DoD (USSF) has also signed an MOU[9] with NASA to collaborate on cislunar activities. The Air Force Office of Scientific Research sponsors fundamental scientific research, including areas relating to space weather.

International Collaboration

The United States has many international space weather partnerships, including with Canada to model the geoelectric field for the combined U.S.–Canada power grid; with Brazil to study the South Atlantic anomaly, scintillations, and plasma bubbles with the Scintillation Prediction Observations Research Task (SPORT) (NASA 2017); with the United Nations to issue radiation advisories for the International Civil Aviation Organization (ICAO); with many countries for the cosmic ray Neutron Monitor DataBase (NMDB; see NMDB 2021) and network; with Spain, Australia, India, and Chile for GONG, which monitors the Sun and provides solar magnetograms and helioseismology measurements; and with the Japan Aerospace Exploration Agency (JAXA) to monitor radiation dosages for the NASA Gateway (NASA 2022).

NASA has increased collaboration with international organizations and universities in the past several years. For modeling developing capabilities, they strengthened the collaboration with the University of Málaga in Spain and with the National Observatory of Athens, Greece, for the development of SEP models as part of the ISEP project. The agency has also started forums with space weather organizations in South America, including uni-

[8] Information about the workshops—Phase I (July 16–17 and September 9–11, 2020) and Phase II (April 11–14, 2022)—along with links to the workshop reports, are available at https://www.nationalacademies.org/our-work/space-weather-operations-and-research-infrastructure-workshop and https://www.nationalacademies.org/event/04-11-2022/space-weather-operations-and-research-infrastructure-workshop-phase-ii-workshop, respectively.

[9] See https://www.nasa.gov/wp-content/uploads/2015/01/nasa_ussf_mou_21_sep_20.pdf.

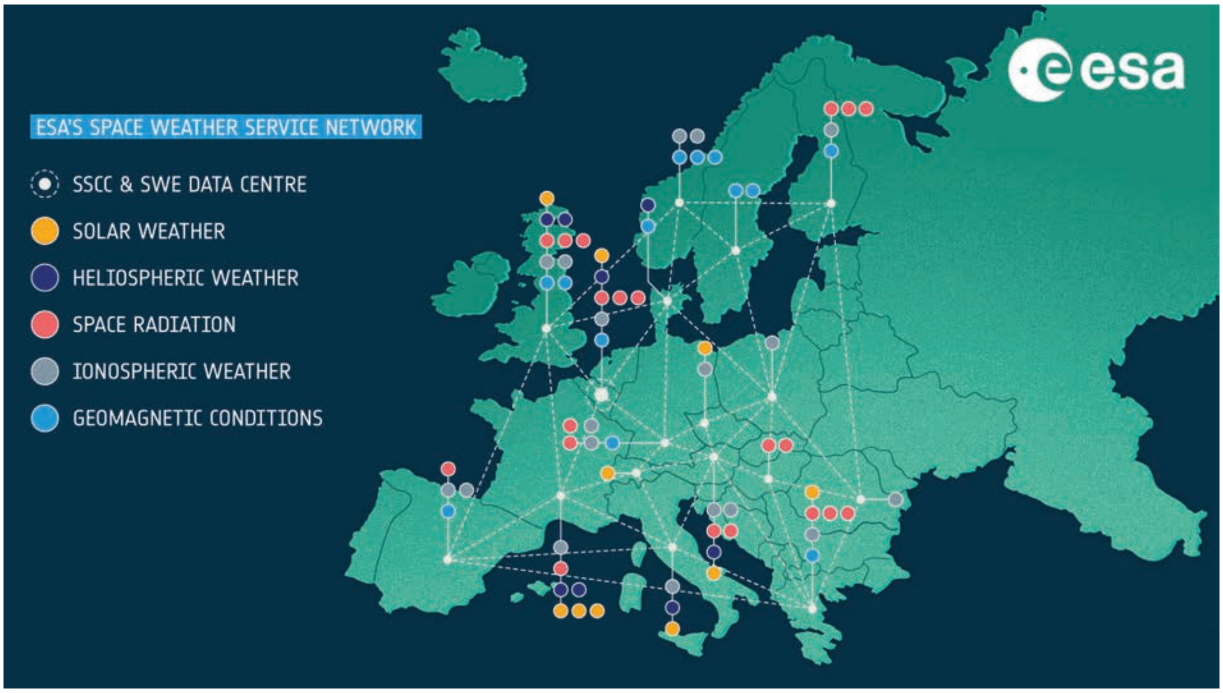

FIGURE E-6 European Space Agency's Space Weather Service Network.
SOURCE: ©ESA.

versities and organizations in Argentina, and in countries in Africa. In addition, there has been an effort across the community to increase international collaboration with efforts like the International Space Weather Action Teams (ISWAT), which are community coordinated efforts hosted by the COSPAR Panel on Space Weather.

The United States has a long history of collaborating on space weather services with the European Space Agency (ESA). Space weather services in the ESA system are based on the federated ESA Space Weather Service Network (Figure E-6). The ESA federation represents a different approach to space weather services than in the United States.

The ESA network includes more than 50 expert groups in ESA Space Safety Programme (S2P) Participating States, carrying out data processing, space weather event analysis, risk assessment, and preoperational service provision. ESA is coordinating the work, development activities, and validation of new European space weather capabilities. All work at service layers beyond the data acquisition is outsourced to European institutes and to industry. ESA leads and coordinates the development of the space-based measurement systems that enable the services. For example, ESA is developing the Vigil mission to be launched in 2031 to add solar and in situ solar wind monitoring capability at the fifth Sun–Earth Lagrangian point (L5). ESA is also developing missions for monitoring of the auroral oval, radiation belts, plasma environment, and upper atmosphere by dedicated small missions and hosted payloads. A large fraction of the tasks in the data acquisition, particularly by ground-based observation systems, are carried out by industry or institutional partners in the Weather Service Network.

ESA is leading the analysis of the European ground-based space weather monitoring systems, initiating activities to fill gaps in the ground-based monitoring capability, and carrying out projects to demonstrate and mature utilization of data from new, operational ground-based assets. Space weather services from the ESA Space Weather Service Network are available from the service portal.[10]

[10] ESA Space Weather Service Network, "Current Space Weather," https://swe.ssa.esa.int.

E.2.2 Status of Specific Operational and Scientific Capabilities

Solar Flares and Coronal Mass Ejections

Solar flares and coronal mass ejections (CMEs), and their associated SEPs,[11] are the major drivers of strong-to-extreme space weather, including geomagnetic superstorms and life-threatening radiation storms. SWPC flare forecasts are currently based on solar active region morphology, climatological rates, and forecaster heuristics. However, flare forecast skill and lead times must be improved to provide truly actionable information for users. Whereas a number of flare forecasting models are being developed in the research community, there remains a high false alarm rate, preventing a reliable forecast. Improvements may come from helioseismology, which has recently advanced to the point that active region emergence on the far side of the Sun can be detected (e.g., Yang et al. 2023a,b).

White light coronagraph imagery provides forecasters with information regarding the direction and speed of propagating CMEs. In particular, the Solar Terrestrial Relations Observatory (STEREO) mission proved the value of having coronal and heliospheric imaging of CMEs off the Sun–Earth line for understanding CME propagation and the forecasting of CME arrival times at Earth. In addition to observations from SWFO-L1 and GOES-19 in conjunction with those from the upcoming Vigil mission, multiple-viewpoint observations off the Sun–Earth line are needed to reduce the forecast uncertainties associated with the CME speed, width, and direction and to monitor associated energetic particles and radiation in support of upcoming interplanetary and Mars missions.

Solar Wind

Variations in the solar wind can also create geomagnetic storms at Earth, although they are typically of lesser intensity (but often of longer duration) than the CME-driven storms. Geomagnetic storms caused by the solar wind can arise as a result of sustained periods of southward-directed magnetic field associated with high-speed solar wind streams (HSSs) and Corotating Interaction Regions (CIRs). These storms enhance currents in the magnetosphere and ionosphere, alter the energetic particle distributions in the radiation belts, and effect change in the ionosphere–thermosphere system, thus impacting end users across a variety of sectors.

Over the past decade, the Advanced Composition Explorer (ACE) and Deep Space Climate Observatory (DSCOVR) spacecraft located at L1 have provided real-time, operational monitoring of the upstream solar wind conditions at Earth for SWPC forecasts and inputs to models. Once deployed, NOAA's SWFO-L1 observatory, a rideshare on NASA's IMAP mission, will take over as the primary operational solar wind monitor.[12] Because solar wind observations from L1 provide less than 1-hour lead time (~10 minutes for the fastest CMEs), modeling is required for more actionable forecasts.

Currently operational at NOAA SWPC are the coupled Wang-Sheeley-Arge (WSA) and Enlil (WSA-Enlil) models, first operationalized in 2011 and upgraded in 2019. They provide a 1- to 4-day prediction of solar wind structures as well as Earth-directed CME arrival times. Driven by GONG line-of-sight photospheric synoptic magnetic field maps, the WSA model calculates the basal solar wind out to 21.5 solar radii and feeds that information to the time-dependent 3D magnetohydrodynamic (MHD) Enlil model, which simulates the resulting interplanetary solar wind speed, density, and magnetic field strength throughout the heliosphere. When used in conjunction with the Cone model, which contains CME timing, location, direction, and speed characterizations, the WSA-ENLIL-Cone model simulates the propagation of CMEs through the ambient medium guiding forecasters of CME arrival time at Earth (and at other locations for NASA mission support).

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[11] The acronyms and descriptions of energetic particle events vary. In space weather forecasting and space radiation operations, solar particle events (SPEs) refer to >10 MeV protons exceeding a threshold of 10 pfu. Energetic solar particle events (ESPEs) refer to >100 MeV protons exceeding 1 pfu. Last, energetic storm particles (ESPs) refer to the energetic particles produced locally at a shock as they travel in the heliosphere. Throughout this appendix, the most general term, solar energetic particle (SEP), will be used. SEPs are far more dynamic but less energetic than galactic cosmic rays, and they produce much of the space weather radiation that can be mitigated by, for example, the consideration of shielding options in the design of spacecraft and radiation shelters.

[12] This paragraph was modified after release of the report to clarify that the SWFO-L1 observatory is a rideshare on the IMAP mission.

Because CMEs are input as hydrodynamic pulses (i.e., with no internal magnetic structure), a forecast of the CME magnetic field magnitude or direction is not possible, severely hampering forecasts of the associated geomagnetic storm intensity. The upcoming ESA Vigil mission will provide in situ observations of the solar wind speed, density, temperature, and IMF at L5, about 4 days before the wind from the same source regions hits Earth. These observations will provide more information for the solar wind models and forecasting the geomagnetic storms on Earth caused by high-speed solar wind streams.

Geomagnetic Field Modeling and Ground-Induced Currents

The Geospace Model, a subset of the University of Michigan SWMF, is currently in use at NOAA SWPC to forecast the geospace environment. It includes a global MHD model of Earth's geospace environment, the Rice Convection Model for the inner magnetosphere, and the Ridley Ionosphere Model. The model was operationalized in 2016 and was upgraded in 2021. The model outputs include forecasts of geomagnetic indices (Kp and Dst) and time-varying ground magnetic field disturbances over regional scales, which can induce surface geoelectric fields that drive Geomagnetically Induced Currents (GICs) in long grounded conductors, including the power grid, pipelines, telecommunication cables, and railway lines. Because the solar wind driver measurements for input to the Geospace Model are obtained at the L1 Lagrangian point, the maximum forecast lead time of the Geospace Model is 10–30 minutes, depending on the solar wind transit time from L1 to Earth. This lead time is not sufficient to give power grid operators actionable warnings of incoming geomagnetic storms, with most operators requiring lead times of at least 12 hours.

Currently, the regional geoelectric fields are nowcast using six real-time U.S. Geological Survey (USGS) magnetometers and Earth-conductivity information. Developed with the cooperation among NOAA, Natural Resources Canada (NRCan), USGS, and NASA, a new U.S.–Canada 1D Geoelectric Field Model (GFM) was released in June 2023. The U.S. portion uses 1D transfer functions defined in physiographic regions (Electric Power Research Institute 2020), and the Canadian portion uses physiographic conductivity models described by Trichtchenko et al. (2019). The new 3D empirical magnetotelluric transfer functions (EMTF) GFM was operationalized in 2020 and uses EMTF from magnetotelluric (MT) surveys across the contiguous United States (CONUS) region (Kelbert et al. 2011). Both of the new 1D and 3D geoelectric field models are significant improvements over the prior model (EPRI 2012). Finalizing the MT surveys across CONUS will ensure complete coverage of the EMTF-3D model for users in all regions.

Currently, models provide only near-real-time magnetic field measurements; the NOAA/USGS GFMs provide no lead time for operators to act on model guidance. To provide actionable guidance to users, models must advance from nowcasting to forecasting. Coupling of the Geospace Model with geoelectric modeling and subsequent power grid impacts in order to provide a forecast lead time has been demonstrated in the research community (Mate et al. 2021).

Ionosphere and Thermosphere

Operational ionospheric/thermospheric information is primarily provided by empirical or physics-based models. Currently, the most accurate and reliable forecasting and nowcasting model of the neutral thermosphere is the High-Accuracy Satellite Drag Model (HASDM),[13] which is run by USSF for operational orbital conjunction (collision) analysis in LEO. HASDM consists of the empirical JB08 model (Space Environment Technologies 2021) and a "dynamic calibration atmosphere" data assimilation system that makes temperature corrections based on comparison of modeled and radar-tracked satellite trajectories every 3 hours to produce daily forecasts of thermospheric conditions with 6-day lead times. The NASA Conjunction Assessment and Risk Analysis (CARA) office as well as DoD and NOAA satellite operations offices receive conjunction data from the USSF, perform refined conjunction assessments, and plan collision avoidance maneuvers for the ISS and other NASA satellite

[13] "High-Accuracy Satellite Drag Model (HASDM)," https://ccmc.gsfc.nasa.gov/static/files/SWW-2014-GEM-CEDAR-Bruce_Bowman_HASDM.pdf.

assets based on this information. Unfortunately, the 80–90 radar-tracked "calibration satellite" trajectories used for near-real-time correction of JB08 temperatures and densities are classified and not available for civilian research or independent operational conjunction assessment (see the section "Emerging Needs for Space Traffic Situational Awareness," below). In addition, because JB08 models only a hydrostatic atmosphere, HASDM cannot accurately predict the rapid density changes associated with geomagnetic storms; the model essentially reverts to a nowcasting capability during the periods in which accurate forecasts are most needed.

At NOAA SWPC, a suite of ionospheric models is used in operations, as follows:

- The physics-based Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics (CTIPe) model provides a global, time-dependent wind vector, temperature, and density of the neutral thermosphere and is used to issue a daily global total electron content (TEC) forecast.
- The Global Total Electron Content (GloTEC) global-scale 3D electron density data assimilation model nowcasts ionospheric conditions in near real time, assimilating ground-based GNSS observations from hundreds of dual frequency receivers around the world in real time as well as radio occultation (RO) observations from COSMIC. GloTEC is being used to evaluate commercial RO data as part of the Commercial Weather Data Pilot to improve geolocation of plasma irregularities and estimates of irregularity strength.
- The coupled WAM-IPE Forecast System (WFS; operationalized in 2021) provides a 2-day forecast of conditions in the ionosphere and thermosphere in response to solar, geomagnetic, and lower-atmospheric forcing. It supports SWPC advisories relating to communication systems and GNSS impacts and neutral density maps used for orbit prediction and space traffic coordination. Coupling WAM-IPE to the Geospace Model to obtain a more accurate conductivity map and to enable two-way magnetosphere–ionosphere coupling is the focus of one of NASA's Space Weather COEs. The assimilation of COSMIC-2 high-rate ionospheric data into the WAM-IPE model to enable GNSS scintillation forecasts is a focus of another COE. Last, another COE is assimilating neutral-density data for thermospheric forecasting.
- The Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting (OVATION) model is an empirical model that uses L1 solar wind velocity and interplanetary magnetic field measurements to calculate a short-term (10- to 30-minute) forecast of the location and intensity of the aurora. OVATION provides an indication of current geomagnetic storm conditions and provides situational awareness for a number of technologies (GNSS/GPS, high-frequency [HF] communications). It is SWPC's most viewed website, by far, owing to the desire of auroral tourists to gauge the location of the aurora on any given night.
- The D-Region Absorption Product (D-RAP) addresses the operational impact of the solar X-ray flux and SEP events on HF radio communication. It uses empirically determined relationships to compute HF absorption and the maximum useable HF frequency (MUF) from GOES satellite space weather data.

In the wider research community, the most advanced physics-based research model of the ITM system is the Whole Atmosphere Community Climate Model—Extended (WACCM-X), developed at the National Center for Atmospheric Research (NCAR) High-Altitude Observatory (HAO). WACCM-X has more advanced atmospheric chemistry and dynamic subroutines than WAM-IPE but lacks the integration of the tropospheric weather forecasting model that WAM-IPE uses for its lower boundary and initial conditions. WACCM-X is the preferred platform for the development of ITM data assimilation frameworks that may be transitioned to the WAM-IPE model for operational forecasting. Currently, HAO and the NASA Global Observations of the Limb and Disk (GOLD) team are working on the assimilation of GOLD global thermospheric temperature and composition data into WACCM-X. In DoD, the NAVGEM-HA (Navy Global Environmental Model—High Altitude) model developed at the Naval Research Laboratory (NRL) is the most advanced whole-atmosphere space weather forecasting model in operational use. NAVGEM-HA includes both tropospheric data assimilation as well as GOLD, ICON, DMSP, and meteor radar data assimilation in the middle to upper atmosphere. Additional empirical ITM models that are in both research and operational use are the NRL Mass Spectrometer Incoherent Scatter (NRLMSIS) model, the Drag Thermosphere Model (DTM), and the Storm Time Empirical Ionospheric Correction model.

Energetic Particles—Radiation Belt, Solar Energetic Particles, Galactic Cosmic Rays

Crewed and robotic exploration, as well as satellite services, are impacted by magnetospheric plasma, radiation belts, SEPs, and GCRs. NOAA SWPC generates products used by satellite operators, including daily reports, the Spacecraft Environmental Anomalies Expert System—Real Time (SEAESRT) model, low-altitude daily belt indices, forecasts, and real-time data. With growth in non-geostationary orbits, especially LEO, the absence of operational global radiation belt and hot and cold electron plasma models is becoming a problem. Currently, radiation belt operational models remain focused on geostationary orbit. Two products are used for geostationary operations: the Relativistic Electron Forecast Model (REFM) for internal charging, which provides 3-day-ahead quantitative forecasts of MeV electron flux at geostationary orbit, and SEAESRT, which provides surface charging, internal charging, single event effects, and event total dose hazard nowcasts for the entire GEO belt and 3 days of forensic conditions for a reference vehicle at 270°E longitude. For plasma effects, SEAESRT is driven by the Kp geomagnetic index because there are no operating alternatives to specify the keV electron plasma that causes surface charging. At NASA, M2M makes space weather anomaly assessments in support of NASA missions using tools developed by CCMC in collaboration with other agencies.

Future human space exploration will occur mostly outside Earth's magnetosphere, where the principal concerns will be SEPs and GCRs.

Currently operational at SWPC is the Proton Prediction Model, a simple, post-eruptive statistical model that outputs the probability of an SEP event based on the associated X-ray flare magnitude and location on the solar disk. Advancements are required to provide accurate pre-event probabilistic forecasts with uncertainty quantification (i.e., actionable forecasts) of SEP timing, intensity, and spectra for locations at Earth and beyond LEO for missions to the Moon and in the future, Mars.

A number of physics-based, empirical, and machine learning (ML) models are being developed in the research community and are being evaluated by NASA CCMC, SRAG, and M2M and NOAA SWPC. In general, SEP models have high false alarm rates and peak intensity predictions with errors over multiple orders of magnitude that must be improved upon for use in operations. To achieve this goal, CCMC, M2M, and SRAG are in constant communication with model developers to improve the forecast and nowcast capability of each model for the ISEP project. Validation of the models in a real-time setting is also ongoing as part of the M2M, SRAG, CCMC, and SWPC activities.

In Earth's atmosphere, GCRs, SEPs, and radiation belt particles create a shower of secondary energetic particles that can endanger airline crew and passengers and potentially cause SEUs in avionics. During large SEP events, this enhanced atmospheric radiation environment poses a hazard for flight crew and passengers, especially for high-altitude flights over the geomagnetic poles. Historically, aviation operators have used the global Level 3 threshold on NOAA's Solar Radiation S-Scale (S3) as an indicator of possible impacts to HF radio communications and human health. In response to user requests for geographically targeted forecasts tailored for the aviation community—as identified in the Abt Associates 2019 report *Customer Needs and Requirements for Space Weather Products and Services* (Abt Associates 2019), NOAA SWPC began issuing radiation advisories for the UN International Civil Aviation Organization (ICAO) in 2019 (Bain et al. 2023). To support these new advisories, the FAA CARI-7 (FAA 2021) aviation radiation model now runs operationally at NOAA SWPC, providing a nowcast of the aviation radiation environment. Moving from nowcasting to forecasting requires reliable forecasts of SEP timing and intensity, as well as a real-time model of solar particle access through Earth's magnetosphere (geomagnetic cutoff).

E.3 PRIORITY GOALS

In this section of the appendix, the panel lists its highest-priority goals for the space weather enterprise for the decade from 2024 to 2033, along with the rationale for these choices. All goals listed in this section are assumed to be achievable within the next decade given sufficient resources and a coordinated effort among federal agencies, academia, and commercial providers. High-priority, long-term goals that have complex challenges and are likely to require more than 10 years to accomplish are addressed separately in Section E.5. The nearer-term priority goals are grouped into two categories that indicate the relative priority of achieving each goal within the next 10 years:

- *Critical:* These goals are the highest priority for investment because their accomplishment would have the greatest impact across a wide range of space weather operations and services.
- *Very Important:* These goals are high-priority investments because their accomplishment would improve space weather operations and services significantly, typically for a select end user group.

Each goal is presented in bulleted text that provides a summary of

- The importance of the goal, including the end users that would primarily be impacted by its achievement.
- Current capabilities. (Note: Additional information on current capabilities is found in the section "Current State of Space Weather.")
- What is needed to make significant progress on each goal.
- The factors considered in the priority categorization of the goal.

Goals within each category are not further ranked in terms of priority; listed order does not imply higher priority for goals within each category.

Some of the panel's goals include a specific forecast time horizon (also called "lead time") target, while others are more general capability goals. When a definitive lead time is displayed, it reflects the panel's opinion of the capability that can be realistically achieved with high accuracy and reliability within the next decade. For example, the solar eruption forecast goal has a specific lead time target of 12 hours and the associated SEP event lead time of 6 hours.

The panel understands that there are currently several eruption forecasts with 24-, 48-, and even 72-hour lead times and that some end users (e.g., power grid operators) would ideally like forecasts of geoeffective eruptions with more than 30 hours of lead time. However, the panel believes that the current long lead time forecasts are not accurate or reliable enough to meet end user requirements; decreasing forecast lead time is the clearest route to improving accuracy and reliability in a complex environment. Furthermore, certain end user needs may prove unattainable given the anticipated advancements in knowledge over the next decade—for example, the ability to monitor, model, and forecast active region evolution accurately over more than 30 hours is unlikely to be achievable in the next decade. To reiterate: When the panel specifies a lead time, it indicates the belief that the target can be achieved with high accuracy and reliability within the next 10 years.

E.3.1 Goal 1

Develop an accurate and reliable 12-hour lead time probabilistic >M1 solar eruption forecast and associated SEP event forecast with 6-hour lead time.

Solar magnetic eruptions are the root cause phenomenon behind extreme and life-threatening space weather events. They are the progenitors of solar flares that cause ionospheric disturbances, CMEs that cause geomagnetic storms and associated thermospheric and ionospheric impacts, and SEP events that can damage or disable satellites and spacecraft and threaten the long- and short-term health of astronauts in worst-case scenarios.

While solar wind HSS and associated CIRs are capable of producing strong (G3 on the NOAA scale) and even sometimes severe (G4) events, the only phenomena capable of generating the 1-in-100-year extreme geomagnetic and/or radiation storms are solar magnetic eruptions. Significantly increasing lead times to enable mitigation of a number of space weather impacts (e.g., communications and navigation interference, power grid destabilization, astronaut health) is predicated on better understanding and forecasting of the timing, direction, and intensity of solar eruptions. The most energetic Earth-directed CMEs can arrive within 12–14 hours, within the error bars of arrival time estimates from current solar wind/CME models. Major SEP events can also penetrate Earth's magnetic field to impact aviation and commercial suborbital operations outside of polar regions.

Currently, SWPC issues 24-, 48-, and 72-hour probabilistic eruption forecasts based on analysis of solar active region morphology, climatological rates, and human-in-the-loop (HITL) modifications with magnitudes based on the associated X-ray flare magnitude, specifically for events with >M1 flares on the NOAA X-ray flare scale. The 24-hour eruption/flare forecasts have been shown to have true skill statistic (TSS) scores of no better than 0.4–0.5 owing to a high false alarm ratio (FAR) that results in low reliability and leads users to ignore these forecasts when making decisions. Automated 24-hour solar eruption forecasts based on statistical and ML techniques currently do no better than HITL forecasts. Skill at 48- and 72-hour lead times has not been analyzed in detail in open literature but is thought to be no better than random prediction because the timescales of active region evolution to eruptive states are on the order of 24–30 hours, significantly less than either lead time. The panel is not aware of any end users who use these forecasts to decide on actions to mitigate the potential consequences of a major solar eruption.

SWPC also issues 24-, 48-, and 72-hour probabilistic forecasts for S1 proton events, defined as ≥10 particle flux units (pfu) for ≥10 MeV protons, with a 24-hour probability of detection (POD) of 0.5–0.7 and declining skill for days 2 (48 hours) and 3 (72 hours). Short-term SEP event warning products have lower lead times of around 10 to 30 minutes (for ≥100 MeV protons) to 1–1.5 hours (for ≥10 MeV protons) but again a relatively high FAR of ~25–40 percent. Some post-eruptive empirical SEP models achieve similar skill with median lead times of up to 2 hours but are not yet fully validated or transitioned into operations.

For many prompt SEP events, increasing the lead time to more than a few hours will allow unprotected astronauts on the lunar surface or in unshielded deep-space environments to retreat earlier to shielded environments resulting in reduced overall accumulated dose. The NASA Moon to Mars Space Weather Analysis Office has worked with the SRAG and the CCMC to deploy more than six research models running in real time, providing outputs for the SEP Scoreboards at NASA and for M2M analysis during Artemis missions. The University of Malaga Solar Energetic Particles (UMASEP) proton forecasting model is currently being evaluated for possible transition to the Space Weather Testbed at NOAA/SWPC.

To achieve realistically actionable lead times, which are required across multiple end user groups, additional progress will be needed in the production of an accurate and reliable probabilistic solar eruption watch product and associated eruption magnitude forecast. Accurate (very high POD) and reliable (very low FAR; near zero Brier Score) forecasts of the occurrence of large solar eruptions (≥M1 flares) will safeguard most (if not, all) of the activities impacted by space weather. As mentioned, solar active regions can evolve to eruptive states on timescales of 24–30 hours. The panel believes that an accurate and reliable 24-hour flare forecast is therefore likely not achievable within the next 10 years as it would require the development of data assimilative solar active region models incorporating near-real-time chromospheric and coronal magnetic field measurements in addition to the lower photospheric–magnetic boundary conditions. Such measurements do not yet exist even in the research realm. However, experiments with machine learning solar eruption models have shown an optimal skill level for forecast lead times between about 6 and 18 hours (Chen et al. 2019). Based on this, an accurate and reliable, data-driven (e.g., using EUV chromospheric and coronal imaging), 12-hour eruption forecast is likely achievable, given sufficient investment.

Lead times on SEP event forecasts do not need to be as long to allow actionable mitigation strategies for astronaut safety, launch go/no-go assessments, and aviation route planning (see also Goal 12) to be put in place. The panel believes that an accurate and reliable 6-hour forecast, particularly for the 100 MeV and above proton energies, is an achievable and meaningful advance that can, with sufficient investment, be realized in the next 10 years. A primary measurement requirement to achieve these lead time, accuracy, and reliability milestones via advanced data-driven or data-assimilative approaches is simultaneous, intercalibrated, full-Sun measurements—including from polar vantage points—of magnetic field and atmospheric structure along with coronagraphic imaging so that active regions can be tracked over their entire lifetime, magnetic connectivity established over longitudinal spans, background solar wind models improved, and CME trajectories relative to surrounding coronal structure established. Intercalibrated means that measured magnetogram flux density values and uncertainties can be linearly calibrated across any pair of observing platforms at resolutions sufficient to feed advanced prediction models. Experience with the GONG magnetogram intercalibration efforts has shown that, at minimum, identical instrumentation, spectral line choice, and data reduction algorithms are required for this condition to be met.

Taking into account the fundamental role of solar magnetic eruptions in driving the most impactful space weather, the large number and degree of impacts posed by SEPs, the significant modeling efforts that have already been made toward this aim, and the high likelihood of making breakthrough progress given sufficient investment, the panel assesses that it is *critical* to achieve this goal within the next decade.

E.3.2 Goal 2

Develop physics-based, data-assimilative, thermospheric neutral-density models, including an integrated modeling framework for predicting LEO satellite and debris trajectories, capable of accurate and reliable forecasts during geomagnetic storms.

Thermospheric neutral density is the largest source of uncertainty in calculations of satellite drag that are needed for predictions of satellite and debris trajectories up to altitudes of about 1,000 km. Accurately predicting the orbital trajectories of LEO satellites and debris is critical in assessing the risk of conjunctions (collisions) between objects in orbit and for planning drag make-up (DMU) maneuvers to keep operational satellites in their assigned orbits.

The number of active satellites and debris objects in LEO has increased significantly in the past 20 years owing to the recent deployment of communications "mega-constellations" such as the SpaceX Starlink system, from the COSMOS–Iridium collision of 2009, and the Chinese anti-satellite missile test of 2007. The USSF 18th Space Defense Squadron at Vandenburg Space Force Base now issues more than 50,000 Conjunction Data Messages (CDMs, or collision warnings) per month to LEO satellite operators, the majority of which are associated with the more than 5,000 Starlink satellites in orbit at 550 km. Most of these warnings are below actionable response thresholds and are triggered primarily by the high uncertainty of satellite track changes in response to solar and geomagnetic activity driving thermospheric density changes. However, an increasing number of these warnings require careful analysis and potential mitigating actions such as orbit maneuvers.

Many LEO satellite operators are now spending on the order of 20 hours per week (half the full-time equivalent [FTE]) analyzing potential collisions with their satellites. This number was less than 10 hours per month prior to the current proliferation of LEO satellites and debris. Most concerning, this increase in workload has occurred during the relatively calm space weather of the previous 15 years; there has not been an extreme geomagnetic storm since the Halloween storms of 2003. Anecdotal accounts of the 2003 storm period from satellite operators indicate that most, if not all, of the orbital catalog was invalidated as satellites were shifted so far from their nominal orbits by thermospheric density increases that they required reacquisition by tracking radars. Space traffic managers reportedly worked 24/7 emergency shifts for 3 days to reacquire satellite radar tracks, and operators struggled to communicate with satellites that were hundreds to thousands of kilometers off their nominal antenna tracks. Similar impacts were apparently experienced in the 1967, 1989, and 1972 extreme storms.

Although no collisions were publicly disclosed during the 2003 storm, today there is an order of magnitude more satellites in LEO, with another order of magnitude increase planned for the coming decade. It is not unreasonable to think that without significant improvements in our ability to predict satellite orbits during geomagnetic storms, a repeat of the 2003 Halloween event could result in a catastrophic chain reaction of collisions as mega-constellations autonomously maneuver based on incorrect CDMs, leading to a cascading chain reaction of collisions termed the Kessler Syndrome.

Currently, there are several empirical models of thermospheric neutral density (e.g., the Mass Spectrometer Incoherent Scatter [MSIS] series of models, the Jacchia-Bowman series of models such as JB08, and DTM) and several physics-based models of the ITM system (e.g., CTIPe, Thermosphere Ionosphere Electrodynamic General Circulation Model [TIE-GCM], Navy Global Environmental Model [NAVGEM], WACCM-X, WAM-IPE, and NAVGEM-HA). The USSF uses the JB08 model with data assimilation enabled by the tracking of about 70 "calibration objects" at various LEO altitudes. The resulting model, the HASDM, is currently the gold standard against which other thermospheric density models ought to be compared. Unfortunately, the JB08 model has very poor forecasting ability, as it assumes a uniform, hydrostatic atmosphere and uses only crude solar wind and geomagnetic activity inputs. During severe geomagnetic storms, the JB08 model reverts to a nowcasting update model and produces inaccurate trajectories for orbital operations planning or conjunction assessments.

In the commercial realm, the Dragster model developed by Orion Space Systems[14] uses an assimilative and multiple-model ensemble approach to forecast thermospheric density, composition, and neutral winds along specific orbital tracks. It is capable of some forecasting skill during storms, although rigorous validation is lacking in the

[14] Orion Space Solutions is now part of Arcfield. See Erwin (2023).

open literature. Of the physics-based models in existence, only WAM-IPE has been integrated into operational use at NOAA/SWPC to provide thermospheric density forecasts to LEO satellite operators. But WAM-IPE has not been validated, and without data assimilation to correct it, the model, like all large physics-based numerical simulation models lacking data assimilation, is inaccurate even during quiet conditions.

Accurately calculating satellite trajectories to ensure safe operations in LEO requires more than just a good thermospheric density model; it also requires accurate calculations of the coefficient of drag (Cd) of satellites and debris objects, detailed knowledge of satellite geometry and attitude relative to the ambient neutral winds in LEO, and solar radiative forcing, particularly for higher LEO altitudes. Calculations of Cd in turn require detailed knowledge of a given satellite or debris object's geometry and materials, atmospheric composition as a function of altitude and energy inputs, and the gas–surface interactions that underlie drag forces in orbit. Current operational trajectory models often assume constant Cd values based on simplified spherical geometries.

There is a critical need to develop an accurate and reliable thermospheric-density model that incorporates advanced data assimilation capabilities and produces a 24- to 48-hour forecast of thermospheric density during geomagnetic storm conditions. Such a model cannot be an empirical hydrostatic model owing to the need for accurate predictions during dynamic storm conditions. Global measurements across a large range of spatial and temporal scales are needed to better understand how solar and magnetospheric inputs combine to drive upper atmospheric dynamics during storms. Moreover, there is still a lack of sufficient measurements to understand how the lower atmosphere (troposphere/stratosphere) and mesosphere condition the upper atmosphere—for example, by the coupling of gravity waves to thermospheric dynamics.

The development of advanced data assimilation techniques that can operate in the data-sparse upper atmospheric regions will also be critical to meeting this goal. In particular, data assimilation systems developed for the data-rich lower atmosphere, such as the well-known 4DVar system, are in general not directly transferable to the highly driven upper atmospheric regions with sparse measurement distributions. Significant investments are needed in a variety of novel data assimilation research programs, including investigations of nonlinear and non-Gaussian ML methods for model parameter and state space adjustments. It has also been shown that data assimilation systems concentrating on ionosphere or thermosphere data sources separately do not produce accurate state vector convergence; a coupled ionosphere–thermosphere system requires coupled ionosphere–thermosphere data assimilation for accurate convergence. In addition, more environmental measurements are needed in the LEO regime at a variety of altitudes and orbital inclinations. For example, a radar tracking calibration satellite fleet like that used for HASDM but designed specifically for civil applications would be beneficial. Last, research into gas–surface interactions and measurements to improve our knowledge of drag forces and Cd calculations is needed so that accurate satellite force models can be deployed.

In summary, the accomplishment of this goal will require an integrated modeling framework that includes the following:

- A data assimilative upper atmospheric forecasting model that is accurate during geomagnetic storms and includes quantified uncertainties that are much lower than current model uncertainties;
- An advanced satellite forcing model that accurately calculates nonconservative drag and solar radiation forces, taking into account Cd and frontal area variation over entire orbits; and
- Improved conjunction assessment calculations and visualization systems that will enable operators to better analyze the increasingly congested LEO environment and make rapid decisions during dynamic conditions such as extreme geomagnetic storms.

It is recognized that only the first of these items is directly related to space weather research; however, the panel includes them to highlight that space weather research must often be closely integrated with other applied science and engineering disciplines to achieve actionable results for end users.

Because of the increasing congestion of the LEO orbital environment, potential for catastrophic damage to increasingly critical space infrastructure, and the central role played by thermospheric neutral-density forecasts in determining LEO resident space object trajectories, conjunctions, debris propagation, and reentry parameters, the panel assesses that it is *critical* to achieve this goal within the next decade.

E.3.3 Goal 3

Characterize and monitor the space weather environment in cislunar space and on the lunar surface in support of the Artemis program.

For activities outside Earth's protective magnetosphere, the primary risk is high-fluence SEP events that have the capability of causing long-term or acute health impacts to human astronauts or destroying spacecraft avionics and control systems. Since the conclusion of the Apollo program, all human space flight activity has taken place in LEO, deep within the protective magnetosphere, and SEP events have not been an extreme risk. However, NASA is investing major resources in the Artemis human space flight program, which aims to have astronauts working on the surface of the Moon in the next decade and setting foot on Mars in the 2030s.

To safeguard the near-term goal of landing astronauts on the Moon in the first part of the decade addressed by this study, it is imperative that NASA characterize and continuously monitor the space weather environment, particularly regarding radiation conditions in cislunar space and on the surface of the Moon. In addition, it is important to note that the Moon is within Earth's magnetotail for several days during every orbit. Here the threat of surface charge build-up from energetic electrons accelerated by magnetotail reconnection events may be a significant risk to astronauts working in cislunar space or on the surface of the Moon. Furthermore, lunar dust may interact with the solar wind or magnetotail, producing a dynamic hazard for lunar surface activities.

NOAA SWPC has supported NASA human exploration activities with space weather services since the Gemini and Apollo mission eras and recently signed an interagency agreement with NASA to continue that support for crewed missions to the ISS as well as Artemis cislunar and surface missions (as well as future missions to Mars). Current NOAA SWPC SEP forecasting services are described in Goal 1. The radiation environment inside a spacecraft in orbit around the Moon or in a habitat on the lunar surface is mainly extrapolated through modeling using assumed SEP spectral energy characteristics and particle transport codes such as GEANT4 (Geometry and Tracking) or HZETRN (High Charge [Z] and Energy Transport). The recent Artemis I mission took many radiation measurements inside the Orion vehicle; however, no SEP event occurred during the mission and the spacecraft did not spend significant time in the magnetotail for studies of reconnection acceleration of surface charging electrons (and in any case, the spacecraft was not instrumented to detect this phenomenon).

In summary, the current ability to accurately and reliably forecast SEP events and their potential impacts to systems and humans in cislunar or lunar environments is severely limited. The Lunar Gateway will be outfitted with the NASA HERMES space weather instrument package on the exterior of the vehicle. When combined with the ESA European Radiation Sensors Array (ERSA; exterior particles and fields) and interior dosimetry array (IDA; interior dosimetry) instrumentation, the measurements will characterize the radiation environment inside and outside the Gateway and have the potential to make significant headway in validating transport codes, improving the understanding of radiation impacts to systems, and providing some measurements that may enable the capability of SEP forecasting at the vehicle.

To characterize the cislunar and lunar surface environments, both exploratory science missions as well as continuous operational monitoring missions are required. These missions will provide the data to validate current and in-development forecasting and nowcasting models predicting radiation environments relevant to the Artemis exploration program; they will also establish the total dose rates expected in long-duration deep-space missions.

In addition to the full-Sun measurements mentioned in Goal 1 to enable continuous active region monitoring and better CME analysis, continuous, multilocation, in situ measurements of energetic charged particles in cislunar space over at least one solar cycle are needed to fully characterize the radiation environment. Continuous space-based measurements of species-discriminated GCR ions are needed to monitor and predict the background radiation environment and extend the historical record started by the Advanced Composition Explorer (ACE) Cosmic Ray Isotope Spectrometer (CRIS) in 1997. Radiation measurements are also required within the vehicles and habitats of the lunar program.

Last, detailed measurements of the plasma environment in cislunar space, with an emphasis on energetic electrons, will significantly advance knowledge of the surface charging risk to astronauts and vehicles while in the magnetotail. Tools that synthesize these measurements and report the radiation environment with any foreseeable risks at locations of interest would support a human presence in cislunar space. Note that the panel's discussion of the requirements for science and monitoring of the Martian environment, and during Earth–Mars transit, is presented in Section E.5, "Long-Term Goals."

NASA's Artemis program is under way, with humans slated to return to the Moon in 2026. Commercial companies are already planning for lunar tourism and will continue to broaden these efforts. Because of the current and continuing expansion of human presence in cislunar space, the panel assesses that it is *critical* to achieve this goal within the next decade.

E.3.4 Goal 4

Develop a 12-hour lead time forecast of CME Bz and a 2- to 3-hour upwind nowcast of other solar wind and CME characteristics at Earth.

The North–South component of the magnetic field of the solar wind and CMEs (so-called Bz) is the main determinant of the severity of geomagnetic storms when these structures impact Earth. Forecasting Bz, particularly for fast incoming CMEs, is critical to support a wide range of end users such as power grid operators and satellite operators, and for input to various magnetospheric, ionospheric, and auroral models and geomagnetic index (Kp, AE, PC, Dst) forecasts that are used in impact models. The dawn-to-dusk electric field, given approximately by the product of Vx (the CME/solar wind velocity in the x direction, where x is in the Sun–Earth [radial] direction) and Bz, is the main driver for dayside magnetospheric reconnection rate that largely determines storm severity. Vx and Bz are therefore the most important solar wind or CME quantities to measure to predict the degree of solar wind–magnetosphere coupling upon impact.

While some end users request a 24-hour Bz/geomagnetic storm severity forecast, the panel feels that this is not achievable with the observations and models planned for the coming decade. In particular, the fastest CMEs that cause the most severe storms can arrive in less than 15 hours. However, the panel believes that an accurate and reliable forecast of Bz sign and magnitude with a 12-hour lead time, accompanied by upstream measurements of CME Bz that afford a 2–3 hour nowcast/warning capability, is achievable in the next decade. Other solar wind parameters, such as velocity and proton density, are also important to determine the full response of the magnetosphere to impact, but they are less critical as forecasting targets.

Currently, forecasting IMF Bz and solar wind parameters at Earth relies primarily on solar wind measurements at the L1 Lagrangian point, which is approximately 1.5 million km sunward of Earth (1 percent of the Earth–Sun distance or 0.99 AU). Such measurements provide a less than 1-hour short-term forecast; for the fastest and most dangerous CMEs, the warning time can be only about 10 minutes. These lead times are insufficient for any operators to take meaningful mitigating actions and are analogous to giving a 30-minute lead time on hurricane arrival to a coastal community.

For CMEs, the radial speed (and hence approximate arrival time at Earth) can be estimated from remote coronagraph observations with an accuracy of about ±100–150 km/s on a range of about 500–3,000 km/sec. Other parameters such as CME magnetic field magnitude and direction are not currently modeled in operations. For example, the operational WSA/Enlil model does not include CME magnetic field; CMEs are modeled only as hydrodynamic perturbations on the background solar wind. Although the panel knows of no definitive validations of WSA/Enlil CME Vx speed predictions, the model seems to generally underpredict Vx speeds with mean absolute errors (MAEs) of no less than 30–40 percent. SWPC issues geomagnetic storm watches with severity estimated on the G-scale based on coronagraph data that indicate the possibility of CME impact at Earth. But without magnetic field information, the severity of the storm is rarely accurately predicted and gross underpredictions of magnitude (e.g., G4 storms occurring when only a G1 was forecast) are common. The probability of detection of current NOAA/SWPC geomagnetic storm forecasts of magnitude "G1 or greater" is about 40 percent and the FAR is about 75 percent (from GPRA reports), making the forecasts essentially unusable for actionable decision-making. The main reason for the low accuracy and low reliability of current geomagnetic storm severity forecasts is inaccurate Earth-directed speed (Vx) predictions and the lack of Bz prediction by any forecast model.

Making progress on this goal requires an approach across two main fronts: (1) To provide an accurate and reliable probabilistic forecast of Bz with lead times on the order of fast CME transit times to Earth, continuous, multiple-viewpoint, remote observations of CMEs combined with realistic numerical models of interplanetary propagation through the background solar wind are needed. (2) To provide an actionable 2- to 3-hour short-term forecast or nowcast of the solar wind and IMF that is to impact Earth, upstream measurements of solar wind and CME speed, density, and vector magnetic field at heliocentric distances of 0.9–0.97 AU are needed. Progress will also require understanding the balance between the accuracy and the lead time of the forecasts, and how to combine remote observations, in situ measurements, and models. Last, to accurately predict the solar wind and IMF conditions that impact Earth's magnetosphere, it is necessary to understand and accurately model how the solar wind and IMF propagates and changes from upstream of L1 to the nose of the bow shock. However, as mentioned in Goal 2, there is no physics-based forecasting model that provides accurate predictions of complex phenomena without data assimilative corrections to update the model state.

Data assimilation into interplanetary CME transport models is extremely challenging given the scale of the measurements required, but may, for example, benefit from multiple spacecraft within and outside of the ecliptic in the upwind position. However, the short 2- to 3-hour lead time of such a correction puts severe limitations on the speed of the transport models. There is thus a need to explore data-driven CME transport models that can be run in seconds rather than hours to enable ensemble data assimilation methods for CME arrival forecasts and Bz predictions. There is also a need to measure the solar wind and IMF close to Earth's bow shock, both to make last-minute corrections to impact-based models and products and to enable nowcasting of storm progression and the issuance of All Clear forecasts (see Goal 6).

Because of the primary role that Bz plays in determining the severity of geomagnetic storms and hence the magnitude of technological impacts, as well as the lack of sufficient lead time given by current models and measurements, the panel assesses that it is *critical* to achieve this goal within the next decade.

E.3.5 Goal 5

Develop nowcast capability for comprehensive characterization of auroral activity, including intensity, boundaries, and energy inputs.

The behavior of auroras, their location, and how they change over time serve as informative indicators of the overall state of Earth's magnetosphere—the magnetic environment around our planet. Specifically, the latitude at which auroral boundaries occur can be used as a proxy for the amount of energy being transferred into the interconnected magnetosphere–ionosphere system and hence serves as a comparative quantification of geomagnetic storm intensity. Furthermore, the intensity of the auroras provides valuable insights into the amount of energy being deposited into the ionosphere and thermosphere and along with the latitudinal boundaries of occurrence serves to demarcate the areas of disturbed ionospheric conditions.

Several crucial user communities are directly impacted by auroral phenomena. These include the operators of power grids, who must contend with potential disruptions from GICs generated by current systems associated with intense auroras. Similarly, those relying on high-frequency (HF) communications, over-the-horizon radars (OTHRs), and GNSS in polar regions are susceptible to the disturbances and signal fluctuations that can arise from joule heating of the ionosphere–thermosphere system associated auroral energy deposition. The auroral oval location alone provides a valuable localization of these operational hazards, and information about the activity within it allows operators to make impact assessments.

Current models, such as the empirical Ovation Prime model and the Operational Geospace configuration of the SWMF, provide predictions of auroral locations and intensities. However, these models lack the necessary level of detail, in both space and time, to serve as inputs to impact models employed by the user communities mentioned earlier. Both models provide a broader, less-specific perspective on auroral behavior that is not actionable for power grid or communications end users. The ground-based THEMIS all-sky imaging network provides high-resolution, but localized and hence disjoint, views of the northern auroral system. In space, the Visible Infrared Imaging Radiometer Suite (VIIRS) instruments on the NOAA Joint Polar Satellite System (JPSS) satellites provide narrow-track nadir views of auroral visible-light emissions on the night side of each polar orbit; however, the revisit times are infrequent and a comprehensive picture of full auroral oval dynamics cannot be synthesized from these observations.

The United States currently lacks an operating, full-hemisphere auroral imaging mission, a situation that has persisted since the termination of NASA's Global Geospace Science (GGS) Polar satellite in April 2008. The joint ESA/China Solar Wind Magnetosphere Ionosphere Link Explorer (SMILE) mission due to launch in 2025 includes the ultraviolet imager instrument (UVI), which will obtain full oval views in the ultraviolet from its planned Molniya orbit, but the availability of UVI data for use by U.S. agencies is in question owing to current legal bans on interactions with Chinese government agencies.

To meet the needs of critical infrastructure operators, real-time information derived from actual auroral imaging is necessary. Both next-generation ground-based all-sky imaging systems as well as space-based multispectral imaging systems are needed to provide sufficient coverage and geolocation accuracies for end users. Unlike current models, which operate on a regional scale, high-resolution (10 km scale) auroral imaging can simultaneously offer a comprehensive snapshot of the entire hemisphere with mesoscale structure resolution, providing high-reliability data about auroral properties and dynamics during geomagnetic storms.

In addition, in situ suprathermal to energetic particle measurements from polar-orbiting LEO satellites are needed to inform particle precipitation rates in ionospheric models. Improvements in polar cap potential specification through the extension of radar systems such as Super Dual Auroral Radar Network (SuperDARN), as well as the continuation of the critical field-aligned current measurements in LEO currently made by the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) system, are also needed. Sustained funding is also necessary to support applied research into advanced models for auroral activity and its effects on the ionosphere–thermosphere systems and satellites in LEO. By specifying how impacts relate to these properties, the information becomes actionable and robust for decision-making that can compile training sets for supervised ML models that could potentially supplant computationally heavy and slow physics-based models for ionospheric impact forecasting.

Because of the increasing congestion of the LEO orbital environment and the critical role played by auroral activity in a number of space weather effects and hazards (including GICs, spacecraft charging, and ionospheric and thermospheric disturbances), the panel assesses that it is *very important* to achieve this goal within the next decade.

E.3.6 Goal 6

Develop reliable probabilistic All Clear forecasts with multiday lead time.

An All Clear forecast indicates that the space weather environment will be quiet, clear, or nonthreatening for a predetermined time period (e.g., 12 or 24 hours). These forecasts are typically issued following major events such as an SEP-causing eruption to indicate the end of the associated threats to human or technological systems. The challenge in issuing an All Clear forecast comes during high solar activity, when there can be multiple eruptions per day. How does one ensure that none of these eruptions cause subsequent geomagnetic storms or SEP events in the direction of critical space operations within a multiday period?

All Clear will have different definitions for different phenomena and end users, but there would be a benefit from an accurate and reliable probabilistic forecast that a given phenomenon will very likely not occur in a specific time window at a specific location. End users in all fields related to space weather could benefit from such a forecast, including human spaceflight, aviation/ATC, power grid operators, satellite operators, RF communications users, OTHR operators, and GNSS users.

The current capabilities for All Clear forecasts are limited. ESA issues a human-in-the-loop All Quiet forecast that is based on the prediction that no Earth-directed eruptions or solar wind disturbances will occur in the specified period. The panel is aware of some models that produce All Clear forecasts—for example, on the All Clear and Probability SEP Scoreboards; however, their skill is currently being assessed. While SEPs are the obvious and necessary initial focus for All Clear development, individual users have needs for All Clear forecasts for nearly every phenomenon. It is worth noting that SWPC does not issue an All Clear forecast of any kind in keeping with National Weather Service (NWS) policy. For example, there is no such thing as an "All Clear tornado forecast" or an "All Clear hurricane forecast" because of the potentially catastrophic consequences of a false negative and associated large legal liabilities. Given the realities of the U.S. legal landscape, it is likely that only the operators of critical mission equipment or human spaceflight missions themselves will be willing to risk issuing All Clear forecasts during active periods of the solar cycle. For example, NASA will likely issue nonpublic All Clear SEP forecasts for use only by NASA human spaceflight missions.

Because All Clear could potentially be applied to all fields of space weather, improvements in essentially all space weather observations and models are desirable to achieve this goal, including coronagraph imagery, X rays, EUV, in situ solar wind plasma, magnetic fields, and energetic particles. From a measurement perspective, continuous full-Sun observations to provide the complete instantaneous state of the Sun to identify solar conditions relevant to All Clear forecasting would be highly beneficial to achieving this goal. In addition, solar radio monitoring for detection of CME-related radio signatures, SEP flux measurements from multiple vantage points around the Sun, solar wind observations upwind of the L1 Lagrangian point, and continuous monitoring of the geospace environment to establish the relevant internal drivers and response states are needed.

Because of NASA's increasing interest in All Clear SEP forecasts as astronauts return to deep-space travel and the broad benefit that reliable All Clear space weather forecasts would have for a wide range of end users, the panel assesses that it is *very important* to achieve this goal within the next decade.

E.3.7 Goal 7

Develop reliable probabilistic forecasting (1 hour) of the geoelectric field with increased spatial resolution (200 km).

The geoelectric field is an important driver of impacts to long-line conducting infrastructure at Earth's surface. The primary impact is power transmission networks which are a critical national infrastructure, but pipelines, undersea cables, railways, and other long conductors can also be impacted. Currents induced in power transmission systems can lead to reduced lifespan (or failure) of transformers and voltage instability and collapse of the network on regional scales. In all cases, the spatiotemporal structure and magnitude of geoelectric field determines critical properties of the network impacts, and thus space weather impacts can be detrimental and in severe cases debilitating to operational systems.

The current NOAA/SWPC Geoelectric Field Models provide deterministic nowcasting based on a geographically sparse set of magnetometer measurements. The model has not been validated, and it is not known to this panel whether any grid operators rely on the model for actionable decision-making. The Geospace configuration of the SWMF in operation at SWPC produces short lead time (15–30 minutes) deterministic predictions of ground magnetic perturbations. This model is also not validated and is known to exhibit significant bias in storm-time geomagnetic perturbation magnitudes. A proof-of-concept study to couple the Geospace and Geoelectric models is being carried out at SWPC but is not currently used operationally for geoelectric field prediction. Until the known biases of the Geospace model are corrected, any geoelectric forecasts based on this model will not be accurate and will likely not be adopted by end users. The ML model of Dst produces a longer lead time (6 hours) forecast with quantified uncertainty and exhibits significantly less bias than the Geospace model.

The relevant nowcast and forecast capabilities need increased spatial resolution to better characterize regional impacts for operators. Meeting this basic need will require a number of basic research components that are detailed in Table E-1. From an applied research perspective, the national magnetotelluric survey needs to be completed with quantified uncertainty established for the transfer function and a similar survey for the U.S.–Canada border region needs to be undertaken to ensure that there is adequate coverage for full-CONUS modeling of the geoelectric field. In addition, the development of probabilistic forecasting models needs to be undertaken with the involvement of grid operators to ensure that the models are accurate, reliable, and thus actionable from an end user standpoint. Direct measurements of the geoelectric field are also needed for model development and validation. Operationally, the magnetometer network across CONUS and Alaska needs to be significantly enhanced to provide regional-scale (100 km) data that can be used in data-driven model development and validation of current and future forecasting models.

Because GIC impacts to the electric power grid and other critical infrastructure are one of the most consequential effects of space weather on a societal scale, and because the current capabilities are not optimally serving a key end user community, the panel assesses that it is *very important* to achieve this goal within the next decade.

TABLE E-1 Summary: Achieving Panel Priority Goals

Goal	Priority Category	Driver or Impact	Basic Research Needs	Applied Research Needs	Operations Needs
1. Develop an accurate and reliable 12-hour lead time probabilistic >M1 solar eruption forecast, and associated SEP event forecast with 6-hour lead time.	Critical	Driver	1. New observing capabilities that include at least: a. Helioseismic observations of subsurface active region formation and flows. b. Chromospheric and coronal vector magnetic field. c. In situ SEP acceleration measurements from multiple locations. d. Distributed near-Sun magnetic field and particle measurements. 2. Well-funded R&A programs for fundamental space weather research studies to improve understanding of solar magnetic eruptions and SEP acceleration.	1. Simultaneous full-Sun measurements of photospheric magnetic field, helioseismic flowfields, and coronagraphic structure. 2. A space weather research program for data assimilative and/or AI/ML models of active region evolution to eruption. 3. Development of small and versatile instruments for energetic particle measurements on rideshares. 4. Development of robust methods for absolute and relative calibration of solar magnetographs.	1. Observations of the western hemisphere of the Sun (e.g., from the Sun–Earth L4 point) for SEP monitoring. 2. Solar photospheric magnetograph and high-energy particle instruments to be included in the next-generation of L1 and GEO space weather platforms. 3. Real-time availability of all relevant space weather data, including a. Simultaneous full-Sun observations of magnetic fields, flows, upper atmosphere structures and flows, and coronagraphic measurements. b. In situ SEP and energetic electron measurements and flare location and timing information. c. Ground and space-based radio measurements of shock formation and particle acceleration signals. 4. Development, validation, and transition of flare and SEP forecast models into operations and establishment of pre-eruptive ensemble modeling capabilities.
2. Develop data-assimilative thermospheric neutral-density models, including an integrated modeling framework for predicting LEO satellite and debris trajectories, capable of accurate and reliable forecasts during geomagnetic storms.	Critical	Impact	1. Measurements from GDC and DYNAMIC as prioritized in the 2013 decadal survey. 2. Fundamental investigations of ionosphere and thermosphere dynamics with emphasis on magnetospheric plasma energy inputs. 3. Development of gas–surface interaction physics research, including the development of advanced drag coefficient models for a wide range of satellite geometries, materials, and attitude profiles.	1. Sustained funding for space weather applied research centers. 2. Developing instruments and missions as pathfinders for operational follow-ons, including a. Small-scale accelerometer and mass spectrometer instrumentation. b. Dedicated rapidly deployable "thermospheric density probes." c. Continuous monitoring of the thermospheric neutral density in LEO across all latitudes.	1. Upper-atmospheric sounding (20–120 km) data from scanning microwave radiometer measurements. 2. Developing a dedicated LEO "calibration satellite" fleet. 3. Research to establish commercial LEO satellite constellation data as assimilation sources for operational thermospheric neutral-density forecasting models. 4. Development of orbital environment model validation, calibration, and verification methods.

continued

TABLE E-1 Continued

Goal	Priority Category	Driver or Impact	Basic Research Needs	Applied Research Needs	Operations Needs
			4. Development of advanced satellite force models that include drag, radiation pressure, and other nonconservative forces. 5. Laboratory measurements of gas–surface interactions in orbital environments.	3. Dedicated LEO satellite mission focused on characterization of gas–surface interactions and other nonconservative forces at multiple altitudes from very low Earth orbit (VELO) to 1,000 km.	
3. Characterize and monitor the space weather environment in cislunar space and on the lunar surface in support of the Artemis program.	Critical	Impact	1. New observations to characterize the changes on the lunar environment, including a. Particle measurements in different shielded environments on the Moon. b. Energetic neutron measurements on the lunar surface. c. Measurements of keV electrons from magnetotail acceleration impacting the lunar surface. 2. Energetic particle measurements distributed throughout the heliosphere.	1. Studies to improve characterizations and predictions of the cislunar radiation environment, including a. Predictions of SEP event profiles for human radiation exposure and SEEs mitigation. b. Variation in the lunar environment owing to topography and secondaries produced in the regolith. c. Modeling of the space radiation environment both external and internal to spacecraft and lunar surface habitats.	1. A space weather monitor at Earth–Sun L4. 2. Onboard human and hardware health particle detectors with wide dynamic range that can make accurate measurements in extreme conditions. 3. Interagency cooperation to support human missions in cislunar space. Specifically, a. Validate and transition space weather models and applications through the space weather proving grounds and testbed for SWPC operational support human space exploration—in particular, solar energetic particle forecast models. b. Develop tools and applications that utilize near-real-time cislunar and lunar surface observations that aid forecast support for NASA human exploration missions.
4. Develop a 12-hour lead time forecast of CME Bz and a 2- to 3-hour upwind nowcast of other solar wind and CME characteristics at Earth.	Critical	Driver	1. Fundamental space weather research to improve heliospheric solar wind and CME modeling and/or propagation techniques. 2. New observational capabilities, including a. Photospheric magnetic field measurements of the polar regions of the Sun to improve solar wind models. b. Photospheric vector magnetogram and coronal magnetic field from multiple locations.	1. Research into data assimilation and ensemble modeling techniques for empirical and physics-based codes of CMEs and solar wind. 2. New observational capabilities to understand the accuracy of measurements at L1 and closer to the Sun for magnetospheric models and solar wind–magnetospheric coupling, including plasma, energetic particles, and magnetic field measurements closer to Earth than L1.	1. Real-time (a) coronagraph images from L1 and at least one more location off the Sun–Earth line (ideally two more locations); (b) radio measurements from the ground; (c) photospheric vector magnetograms from the ground, Earth's vantage point (L1), and one more location east of the Sun–Earth line; (d) EUV measurements from Earth's vantage point and one more location east of the Sun–Earth line; (e) heliospheric imager measurements from at least one location off the Sun–Earth line (ideally two locations).

			c. Coronagraph and heliospheric imagers observations of CMEs from multiple vantage points. d. IMF and particle measurements from locations throughout the heliosphere for data assimilation into models.	3. Technology demonstration to raise the TRL of solar sail technology.	2. Improved operational heliospheric solar wind modeling and/or propagation techniques for CMEs, including their magnetic field, and improved solar wind tracking, tomography algorithms/models, assimilation techniques for remote observations.
5. Develop nowcast capability for comprehensive characterization of auroral activity, including intensity, boundaries, and energy inputs.	Very Important	Driver	1. Support utilization of an augment to the HSO that allows for simultaneous observations of multispectral auroral imaging from the ground and space alongside suprathermal to energetic particle measurements from LEO.	1. Sustained funding for applied research into advanced models for auroral activity and its effects on the ionosphere–thermosphere systems and satellites in LEO. 2. Support development of next generation ground-based auroral observing technologies. 3. Support continued observation of polar cap potential via technologies such as SuperDARN. 4. Support observations of field aligned current patterns through approaches like AMPERE.	1. Deploy a set of space-based observatories providing real-time, comprehensive (i.e., full oval) observations of the auroral ovals in both northern and southern hemispheres simultaneously and continuously. Note that far ultraviolet (FUV) wavelengths are nominal for such observations because those can be made in both sunlit and dark hemispheres.
6. Develop reliable probabilistic All Clear forecasts with multiday lead time.	Very Important	Driver	1. Studies and modeling of the physical processes that drive space weather, including the physical processes that drive solar eruptions, propagation of structures and particles in the heliosphere, arrival of structures and particles at Earth, and corresponding impacts in the magnetosphere–ionosphere–atmosphere system-of-systems and on the ground.	1. Identification of the key parameters and observables that allow for reliable All Clear forecasts. Development of models relevant to the All Clear state and conditions that result in the transition from All Clear to Not Clear states. 2. Multiday All Clear operational forecast models for the current R, S, and G space weather scales with a plan for expansion to meet new and evolving user forecast needs.	1. Continuous full-Sun observations, including the polar regions, to provide the complete instantaneous state of the Sun without gaps to identify solar conditions relevant to All Clear forecasting. 2. Continuous ground- and space-based radio measurements. 3. In situ SEP flux measurements from multiple locations. 4. Solar wind monitors sunward of L1 or ahead in the Parker spiral. 5. Monitors throughout the geospace system-of-systems for all relevant internal drivers plus radiation, magnetospheric, ionospheric, thermospheric, atmospheric (e.g., secondary radiation at aviation altitudes), and ground/GIC observables.

continued

TABLE E-1 Continued

Goal	Priority Category	Driver or Impact	Basic Research Needs	Applied Research Needs	Operations Needs
7. Develop reliable probabilistic forecasting (1 hour) of geoelectric field with increased spatial resolution (200 km).	Very Important	Impact	1. Probabilistic spatiotemporal modeling methods and their application to auroral current systems, geomagnetic disturbances, and solar wind drivers for geospace modeling. 2. Fundamental space weather research studies to characterize and quantify the following: a. Telluric currents and their contributions to magnetic perturbations. b. Auroral drivers of meso- and small-scale current systems that drive geomagnetic disturbances. c. The necessary and sufficient conditions for substorm onset and the predictability of substorms. 3. Spatially dense magnetometer observatories at midlatitudes to characterize the spatiotemporal geomagnetic disturbances driving geoelectric field and enable validation of predictive models. 4. Sustained development of coupled models of the geospace environment and of new methods to provide reliable probabilities and multiple realizations of higher-dimensional predictions, incorporating new approaches in data science and data assimilation. 5. Quantification of event likelihood and hazard impacts for geoelectric hazard.	1. Completion of the magnetotelluric survey of the United States and full characterization of the uncertainties associated with the transfer functions. 2. International collaboration to complete a similar survey north of the United States–Canada border; this would significantly augment the value of the U.S. survey. 3. R2O support for probabilistic forecast models of geoelectric field and other tools developed in tandem with power transmission end users. 4. Coordinated gathering, dissemination, and archiving of GIC, magnetic disturbance, and geoelectric field measurements, following open science best practices. 5. Support and provide geoelectric field measurements for model development and validation.	1. Increased spatial resolution magnetometer observations to characterize, at regional scales, the spatiotemporal geomagnetic disturbances driving geoelectric field at midlatitudes, improve nowcasting, and enable validation of predictive models.

			6. Development and validation of probabilistic models of geoelectric field at regional scales, and tools producing multiple realizations of spatiotemporal geoelectric field. 7. Observations to resolve direct connections between in situ magnetospheric activity and structures and auroral activity and features, providing a pathway to using auroral imaging in hazard zone predictions and resolving the phenomena driving the mesoscale current systems responsible for intense geoelectric fields.		
8. Develop a reliable probabilistic forecast of surface charging (3-day lead time), internal charging (28-day lead time), SEE (6-hour lead time), and event total dose (1-day least time) for all orbits.	Very Important	Impact	1. Fundamental science modeling of upstream drivers (CMEs, SEPs, high-speed streams) and magnetospheric particle populations (hot electron plasma, radiation belt particles, geomagnetic cutoffs). 2. Additional scientific observations of hot electron plasmas and geomagnetic cutoffs (with energy, species, and angular resolution). 3. Supporting data sets to contribute to the physical processes governing the hazardous particle populations: ULF and VLF waves and DC fields.	1. Real-time solar eruption and the consequent SEP and CME modeling to support all forecast aspects of this goal. 2. Real-time radiation belt modeling to meet the 28-day internal charging forecast lead time. 3. Real-time electron plasma modeling in the magnetosphere: plasmasphere, ring current, plasma sheet, and aurora, to achieve the surface charging forecast. 4. Geomagnetic cutoff forecasts needed to achieve a 6-hour SEE forecast. 5. Flight observations of vehicle charging itself to improve models that assess charging risk given a forecast environment. Many of these observations can be obtained opportunistically from missions for which they complement or supplement the science (e.g., through existing or hosted payloads). 6. Targeted missions specifically to study charging and radiation effects. One example such mission would study Spacecraft Charging At High Altitudes (SCATHA for LEO).	1. Continuing real-time upstream solar wind monitoring. 2. Operationalizing improved interplanetary input forecasts (CMEs, SEPs, and high-speed solar wind). 3. Operationalizing models and decision aids developed earlier.

continued

TABLE E-1 Continued

Goal	Priority Category	Driver or Impact	Basic Research Needs	Applied Research Needs	Operations Needs
				7. Long-term observations whenever possible to enable probabilistic and AI/ML models. 8. All the scientific observations noted elsewhere to improve forecasts of solar eruptions and their interplanetary consequences (CMEs and SEPs). 9. Development of real-time data-assimilative models of the radiation belts, ring current, plasma sheet, aurora, and geomagnetic cutoffs. 10. Tools that can evaluate the environment at a satellite/vehicle location or along its trajectory, often by projecting from the natural coordinates of a model to the physical coordinates of the satellite/vehicle. 11. Decision aids that translate these localized environments into likely impacts on satellites and vehicles. 12. Decision aids needed specifically for launch, given that the launch trajectory slips forward in time when the launch is held.	
9. Develop an accurate (to within ±20 percent) 6-month to 1-year forecast of the solar activity cycle as quantified by sunspot number.	Very Important	Driver	1. Improvement of solar dynamo models based on observations of all solar longitudes, including the polar regions, to fully understand the relationship between sunspot number and solar activity of interest.	1. Design of missions involving long-duration human spaceflight (e.g., lunar surface missions and Mars missions).	1. Monitoring for DoD applications and missions. 2. Satellite drag calculations for missions in LEO orbit. 3. Managing/planning safe spacecraft reentry.
10. Develop a robust reanalysis capability for forecast/nowcast models with established community standard input data sets for all key space weather drivers and impacts.	Very Important	?	1. Data-assimilative models and model-run archives. 2. International partnerships for trusted long-term data sets. 3. Simulations that can run for more than 1 solar cycle. 4. Extended simulations to cover complete geophysical domains.	1. Establish a clearinghouse for massive solar-cycle length simulation results. 2. Develop standard file formats and extraction/projection software for applications and validations. 3. Continue long-term observations.	1. Continue long-term space-based observations. 2. Enhance metadata standards to include more context for verification and validation. 3. Archive and disseminate operational model outputs.

11. Develop 30-minute to 1-hour lead time forecasts of transionospheric and skywave mode HF radio wave signal impacts (e.g., ionospheric scintillation, absorption) in polar, midlatitude, and equatorial regions.	Very Important	Impact	1. Fundamental studies of ionospheric electron density structuring, drivers, and associated impacts on specific users. 2. Improved models of 3D, time-evolving ionospheric electron density. 3. Auroral transport and ionospheric models sufficient to enable understanding of particle precipitation on ionospheric structure and GNSS signal propagation in the polar ionosphere.	1. Increased number of RO profiles/day. 2. Enhanced probabilistic models of electron density impacts associated with different drivers (flares, substorms, etc.). 3. Funding opportunities for advancement of ground-based observational capacity, and user needs specifications. 4. Lower barrier of usage for GNSS ocean buoy network data, and expanded network coverage to optimize for data-assimilative models. 5. Available end user data sets for use in space weather research for development of impact-specific models and forecasts. 6. Forecast tools capable of predictions of electron density structures and associated user impacts in different regions (high-latitude, midlatitude, etc.). 7. Continued support for ground-based GNSS instrumentation program, and enhancement of RT data streaming.	1. Development of a comprehensive global network of GNSS TEC measurements with common data interfaces and real-time data availability, including ocean buoy network optimization and associated data pipelines.
12. Develop an accurate aviation and reliable radiation nowcast and forecast for airline operators during large SEP events.	Very Important	Impact	1. Improved models of ionizing radiation in the heliosphere, magnetosphere, and atmosphere. 2. Improved characterization of the geomagnetic field and corresponding energetic particle access. 3. Improved forecasts of SEP timing, intensity, and spectra. 4. Improved understanding of radiation belt trapped particle precipitation into the atmosphere.	1. An observing system experiment (OSE) to determine the optimal configuration of the ground-based neutron monitor network. 2. Airborne measurement campaigns to increase measurements of linear energy transfer spectra and total ionizing dose, particularly during SEPs, to improve and validate aviation radiation models. 3. Investigation of new and alternative air shower measurement techniques for improved SEP energy and composition analysis.	1. Rapidly deployable aerial radiation measurement platforms to autonomously patrol high-latitude, high-altitude commercial aviation routes during major multiday SEP events. 2. Operationally supported measurements from the ground-based neutron monitor network. 3. High-energy in situ energetic proton and alpha measurements from, for example, the GOES spacecraft. 4. Direct measurements of the relevant energetic particle populations precipitating into the atmosphere. 5. A real-time nowcast and forecast model of geomagnetic cutoffs.

NOTE: Acronyms are defined in Appendix H.

E.3.8 Goal 8

Develop a reliable probabilistic forecast of surface charging (3-day lead time), internal charging (28-day lead time), single event effect (SEE; 6-hour lead time), and event total dose (1-day least time) for all orbits.

Surface and internal charging of satellites and spacecraft owing to charged particle surface accumulation or penetration can lead to catastrophic discharge events that can damage or disable the vehicle. Surface charging and discharging are frequently seen on satellite solar panels and over time can lead to significant reductions in vehicle power availability. Single event effect (SEE) damage can occur when energetic protons penetrate to the memory or processor chips of a vehicle's electronics boards, leading to incorrect commands being processed or corrupted memory locations ("bit flips") causing unintended vehicle behavior. SEEs can also fully disable vehicles on worst-case occasions. "Event total dose" refers to the accumulation of energetic charged particles in vehicle materials during transient space weather events, which can affect the function of logic gates and other microcircuit components. The end users affected by this goal are satellite operators, human spaceflight operators, and launch operators. They are impacted by radiation and plasma in space, which can cause satellite and vehicle anomalies and poses a risk to human crews.

The current capability is broad, categorical likelihood forecasts for the NOAA Space Weather Scales for geomagnetic storms, solar flares, and solar particle events. For geosynchronous orbit, there is also a quantitative 3-day forecast of the internal charging electrons (via the Relativistic Electron Forecasting Model) and a nowcast identifying the relative risk for each of the four hazards.

While NOAA's SEAESRT tool provides the quantities called for by this goal, it does not incorporate any forecast information, and it can be applied only to geostationary orbits. This goal explicitly calls for expanding this type of capability to forecasts for all orbits.

Results in the literature show that probabilistic research models are beginning to be skillful at lead times on the order of 3 days for surface charging indicators like Kp; real-time models of the hot plasma electrons are just beginning to take shape and represent a stretch goal. Internal charging models of MeV electrons are showing skill at an entire solar rotation. SEE and total dose models depend on solar energetic particle forecasting, with total dose having somewhat longer time horizons because it is an SEP event-cumulative effect.

Because satellite failures remain one of the costliest impacts of the variable geospace environment, and because providing more useful and actionable services to satellite operators would require relatively little investment to achieve significant progress, the panel assesses that it is *very important* to achieve this goal within the next decade.

E.3.9 Goal 9

Develop an accurate (to within ±20 percent) 6-month to 1-year forecast of the solar activity cycle as quantified by sunspot number.

The solar activity cycle is a general characteristic of the long-term magnetic variation of the Sun and the related eruptive activity that can be a space weather concern. Predicting the gross characteristics (sunspot maximum, peak date, duration) of the cycle is of interest to spacecraft designers (e.g., predicting satellite drag over the course of a mission to estimate reentry timing) as well as designers of missions involving long-duration human spaceflight (e.g., Mars missions; GCR intensities are generally anti-correlated with sunspot number over the course of the cycle). Progression of the solar cycle over the next 6 months to 1 year is of particular interest in managing/planning safe spacecraft reentry. Although the sunspot number and the solar radio 10.7 cm flux (a proxy for solar EUV irradiance, commonly referred to as the F10.7 index) are typically used as indicators of the solar magnetic activity cycle, it is not clear that these are the best indicators for long-term space weather–related impact forecasts. For example, while the sunspot number for cycle 25 is increasing significantly above the prediction for this phase of the cycle, the actual solar activity of space weather interest (e.g., large eruptions and SEP events) is significantly lower than would be expected from comparing the sunspot number with previous cycles at the same phase.

Whole cycle predictions are generally either extrapolation of empirical relationships (e.g., peak versus onset rate statistically determined from previous cycles, precursor indicators such as measured magnetic flux at a specific time/location) or models of the solar dynamo or global flux transport. In general, NOAA provides a composite sunspot number and F10.7 radio flux prediction based on a consensus of predictions from numerous published works, employing a variety of methods, during the solar minimum period preceding a given cycle. The capability to update the prediction based on the functional form of the consensus model, with peak timing and amplitude adjusted to match observed sunspot number progression in the cycle, was recently released by NOAA.

Shorter-term 45-, 27-, and 3-day F10.7 forecasts from SWPC currently use recurrence and forecaster augmentations for ARs rotating on/off the disk; LEO satellite operators use them to predict drag conditions and hence orbital trajectories. There is also the "Schatten model," which issues a sunspot number prediction several solar cycles into the future. Alarmingly, this model, which has been demonstrated to have extremely low-skill prediction, and crude thermospheric density models tied to the sunspot predictions, are being used by satellite operators to calculate expected mission lifetime and reentry dates for LEO satellites. This illustrates the maxim that end users will "use whatever they can get" when trying to make important decisions that depend on estimating future space environment conditions.

Current predictive capabilities are hampered by a limited understanding of the solar polar magnetic field and surface and the subsurface flows that are believed to play a key role in the dynamo generation of magnetic flux in each cycle. Better dynamo models based on measured surface and subsurface global-scale flows in the polar regions are needed, as well as simultaneous observations of all solar longitudes, to enable observation of all eruptions, not just the ones on the Earth-facing disk. The measurement need can be met by developing full-Sun observing systems that include both magnetic field and helioseismic observations to measure surface and subsurface magnetic structures and associated flows. There is also a need to study the relationship between sunspot number and solar activity of interest and to move to a long-term prediction of impactful phenomena related to sunspot activity. To address the satellite operator mission design requirements, there is a need to develop multicycle predictions that are at least marginally accurate and have associated quantified uncertainties.

Because the solar magnetic cycle is the primary origin of space climate variability, and because the current one-time full-cycle-length forecasts do not provide reliable and accurate, and therefore actionable, information to mission planners, satellite operators, and other key end users, the panel assesses that it is *very important* to achieve this goal within the next decade.

E.3.10 Goal 10

Develop a robust reanalysis capability[15] *for forecast/nowcast models with established community standard input data sets for all key space weather drivers and impacts.*

Reanalysis refers to the process of creating a long-term reconstruction of the state space in the space weather environment, typically, but not exclusively, generated with data-assimilative numerical simulation models. End users of this process include satellite/vehicle anomaly analysts and designers, who use reanalysis to refine data from the past that determine either specific conditions during a past or ongoing mission or to establish cumulative and worst-case transient design environments. Reanalysis is also a key process in improving forecasting models—for example, when new data sources become available, errors in observations are identified and corrected, or potential model improvements need to be validated. Furthermore, it is likely that the reanalysis period will include challenging events and thus illuminate model performance gains (or losses).

Reanalysis is a mainstay activity in tropospheric weather forecast model development. For example, the NASA Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) (Bosilovich et al. 2024) is a large weather model output database containing atmospheric parameters from 1980 to the present that have been improved by inclusion of recent NASA satellite observations assimilated into a numerical prediction model. In space weather, the closest analog to tropospheric reanalysis is limited to a handful of papers reporting long-term numerical simulations, usually not data assimilative, and some studies that involved simulating every storm during a long time interval. Such "free running" simulations without data assimilation would not generally be recognized as reanalysis runs by tropospheric weather researchers because they do not include improved input data or specific model improvements demonstrating superior state space specification.

[15] The capability should be robust in the sense that it is not dependent on a small group's effort to create and maintain but rather is spread across several groups that are well funded through standard mechanisms.

What is needed are standard state space models of the magnetosphere and the ITM system spanning many solar cycles. These reanalysis runs would be based on state-of-the-art numerical simulation models and include data assimilation to correct the models to realistic states. These reanalysis studies must also include integrated reanalysis runs of the lower atmosphere in recognition of the coupling between lower- and upper-atmospheric dynamics. A primary need for the realization of this goal is the support of an applied research program designed to fund such studies; current NASA and NSF programs do not fund such studies owing to the perceived lack of basic research "scientific discovery" potential, and the NOAA space weather program lacks an applied research element. When space weather reanalysis data sets are created, it is important to emphasize that they need to be publicly accessible in open repositories for use by the entire space weather research and forecasting community, including commercial providers of space weather products and services.

Because the subfield of systematic reanalysis has been shown to be one of the key drivers of meteorological model improvements, and because the investment to achieve significant progress in the space weather domain would be modest, the panel assesses that it is *very important* to achieve this goal within the next decade.

E.3.11 Goal 11

Develop 30-minute to 1-hour lead time forecasts of transionospheric and skywave mode high-frequency radio wave signal impacts (e.g., ionospheric scintillation, absorption) in polar, midlatitude, and equatorial regions.

Ionospheric structuring and dynamics are critical to technologies that rely on high-frequency (HF) radio wave signals across the civil, commercial, and military domains. This includes transionospheric signals for satellite communication or positioning, navigation, and timing (PNT) services, and skywave-mode (reflected off the ionosphere) propagation utilized for HF communications (e.g., emergency management systems) and OTHR and geolocation systems. In all cases, the spatial/temporal structuring and magnitude of ionospheric electron densities determines critical properties of the utilized signals (e.g., path, absorption, noise) and thus space weather impacts can be detrimental, and, in severe cases, debilitating to operational systems.

Current nowcast/forecast capabilities include real-time modeling of ionospheric absorption for HF communications (skywave) such as NOAA's D-Region Absorption Prediction (DRAP) model, as well as the GloTEC data assimilation model and WAM-IPE ionospheric model.

As the use of GNSS and satellite communications increases along with emerging advancements in OTHR and other skywave mode technologies, there is an increased reliance on HF signals within safety-critical systems—for example, autonomous aircraft and defensive radars. Moving forward, user requirements are already pushing beyond current nowcast/forecast systems toward higher temporal and spatial scale nowcasts, with a need for more capable probabilistic forecasts dedicated to user communities.

Developing this capacity will require significant investment in basic research to enhance coupled ionospheric models capable of interregion/interdomain coupling (e.g., high-latitude ionosphere–magnetosphere coupling) and with sufficient temporal/spatial resolution to capture key phenomena or proxies with space weather impact (e.g., TEC spatial gradients driving GNSS scintillation at auroral latitudes). In consort with model development, comprehensive high-value data must be available, including ground- and space-based measurements of ionospheric electron density or associated proxies. This requires a continuation of current ground-based operations, an expansion of ground-based coverage in key geographic areas, an expansion of satellite-based radio occultation data sources, and an advancement of real-time systems to reduce data latency (across ground and space) to support operational systems.

Because ionospheric interference is one of the most prevalent impacts of space weather on ground- and air-based communications as well as over-the-horizon radars, the panel assesses that it is *very important* to achieve this goal within the next decade.

E.3.12 Goal 12

Develop an accurate and reliable aviation radiation nowcast and forecast for airline operators during large SEP events.

Radiation penetration to airline altitudes during major SEP events is a potentially significant hazard to airline passengers and crew, with crew members at heightened risk due to their likely more frequent exposure.[16] This hazard is particularly acute for the polar route flights that traverse areas of low magnetic rigidity, enabling deep penetration of energetic protons into the stratosphere. The highest-energy SEP protons (energies in the 500 MeV–GeV range) can also create secondary particle showers that lead to high-energy charged particles and neutrons penetrating to very low altitudes and even to the ground (so-called ground-level enhancements, or GLEs). With sufficient warning or timely enough nowcasting of ongoing SEP events, airlines can reroute or cancel polar flights and thus decrease or prevent radiation exposure of passengers and crew. During an extreme SEP event, there is a chance that even low-latitude flights at sufficiently high altitudes would experience some radiation exposure. The development of an accurate forecast and timely nowcast capability is considered a major goal of space weather research.

Aviation radiation models typically run as a pseudo nowcast, with latencies of 10–20 minutes, and are based on operational energetic charged particle measurements made by the GOES satellite. Post facto radiation dose estimation for aviation routes is based on models that rely on data from ground-based neutron monitors (which are not currently operationally supported and can have data latencies of tens of minutes), together with particle data from the operational GOES Solar and Galactic Proton Sensor (SGPS) instrument to infer charge particle fluence at aviation altitudes. GOES particle data alone are not sufficient owing to their maximum differential energy ceiling at 500 MeV for protons. Consequently, large uncertainties arise from poor characterizations of the high-energy portion of SEP spectra having limited spectral resolution at energies >500 MeV. Instead, fits to neutron monitor measurements are required to infer the SEP spectrum incident at the top of the atmosphere. As discussed in Goals 1 and 3, current SEP forecasting models are inaccurate and unreliable and thus not used by airline or military flight planners. Also, as discussed in Goal 6, there is currently no All Clear declaration or forecast capability, both of which would benefit commercial and military aviation operations.

Research is required to improve radiation models that transport ionizing radiation through the heliosphere, Earth's magnetosphere, the neutral atmosphere, and aircraft structures to predict, and provide uncertainties of, human radiation exposure and SEEs in electronic systems. New systematic measurements of linear energy transfer (LET) spectra and total ionizing dose, from a variety of airborne platforms (e.g., balloons, aircraft, and uncrewed aerial vehicles [UAVs]) are required to better understand, model, and validate the atmospheric radiation environment within aviation systems. An improved real-time characterization of the geomagnetic field is required to improve the accuracy of model outputs in regions close to the open/closed field boundary where polar latitude flights between the continental United States and Europe operate and estimates of dose rates currently contain uncertainties of an order of magnitude or more during the most impactful events. Furthermore, improved forecasts of SEP timing, intensity, and spectra are needed to achieve actionable lead times for airline operators.

Because of the growing demands from the aviation industry for forecasts of the radiation environment at aviation flight levels, the potential impacts on human health during large SEPs, and current nowcasts containing limited actionable information with large uncertainties, the panel assesses that it is *very important* to achieve this goal within the next decade.

Figure E-7 displays the panel's assessment of the value and required investment for each of the priority goals discussed here. Table E-1 summarizes the information in this section, showing each of the goals, the panel's judgments as to their importance, and what is required to achieve these goals, broken into categories of basic research, applied research, and operations.

E.4 STRATEGY TO ACHIEVE PRIORITY GOALS

After examining strategies for achieving the priority goals outlined in the preceding section, the panel identified several cross-cutting and agency-specific challenges that, if left unaddressed, will hinder their achievement within the next decade. In this section, the panel provides the context that informs this view, followed by the specific cross-agency and agency-specific strategies.

[16] This paragraph was modified after release of the report to clarify SEP exposure among airline crew members.

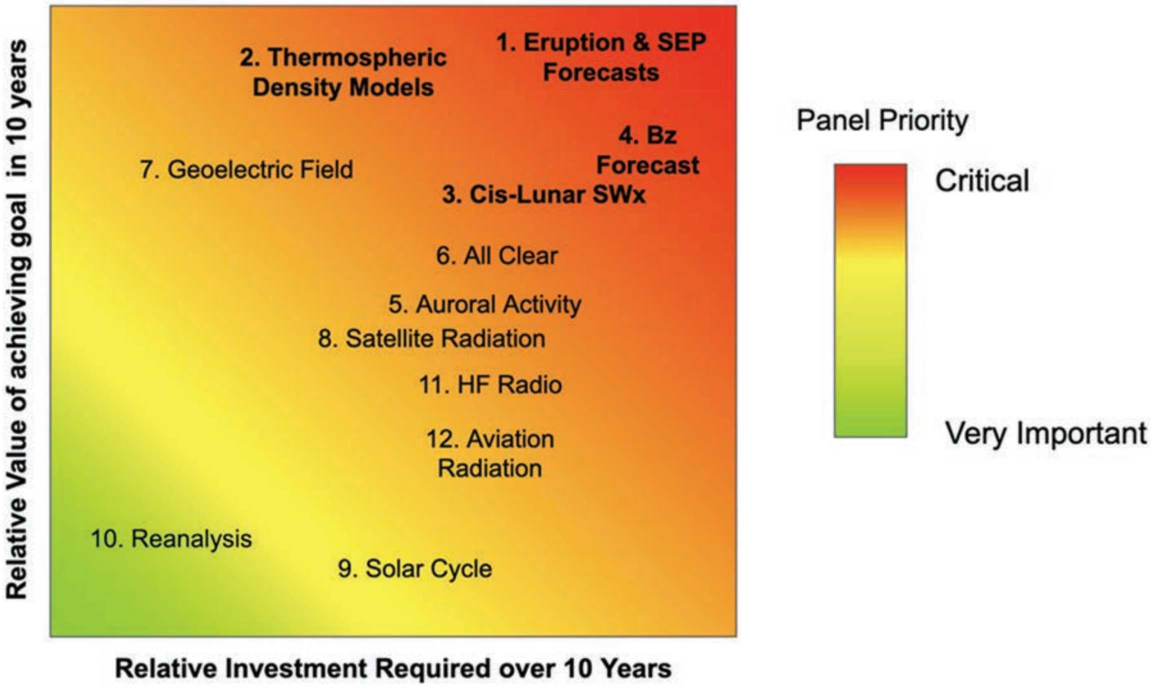

FIGURE E-7 Value of achievement versus required investment estimates for each of the priority goals described above. Each goal is represented by its number and a shortened title. The color scheme roughly corresponds to the panel evaluation of the goals as *critical* or *very important* to achieve within the next decade. Investment required increases to the right; value of goal achievement increases upward. Both investment required and value of achievement are somewhat subjective; no detailed cost-benefit analysis was performed in making this diagram.

E.4.1 Context

The growth in technological systems impacted by space weather has been accompanied by an ever-increasing need for space weather information. The U.S. space weather enterprise is spread over multiple agencies, academic institutions, and the commercial sector. As a result, emerging challenges, such as space debris characterization and mitigation and LEO space traffic coordination and management, are not always well integrated into existing programmatic structures. The panel recognizes that several committees have been established to address this problem—namely, the Space Weather Operations, Research, and Mitigation (SWORM) subcommittee of the NSTC, which is advised by the Space Weather Advisory Group (SWAG); the NASA Space Weather Council, which discusses issues specific to NASA; and the National Academies' Space Weather Round Table, which discusses enterprise-wide challenges in the scientific realm. While the advisory committees offer valuable strategic insight, the SWORM subcommittee is the only group with the authority to recommend cross-agency implementation actions to the Executive Branch.

In agreement with the 2023 SWAG *Findings and Recommendations to Successfully Implement PROSWIFT and Transform the National Space Weather Enterprise Report* (hereafter referred to as the SWAGF&R23; NWS 2023), Finding 1, the panel recognizes the need to appropriately fund the federal space weather enterprise, "To implement PROSWIFT actions, perform the codified roles and responsibilities, or appropriately address the risk space weather poses to the Nation." The panel supports the SWAGF&R23 finding that the "Executive branch should work with Congress to identify new and sustained funding to address these shortfalls" and "Ensure OSTP staffing and White House–led prioritization and coordination across the national space weather enterprise" to meet the needs of a growing economy dependent on space weather information and to improve our space weather readiness as a nation.

The U.S. space weather enterprise does not typically share publicly the results of cost-benefit studies of space weather missions or architectures. Such analyses, known as observing system experiments (OSEs; quantifying performance of a new observatory in an operational framework using real data) or observing system simulation experiments (OSSEs; quantifying performance of a new observatory in an operational framework using simulated data), are routinely carried out in the tropospheric weather enterprise. The lack of formal OSE and OSSE capabilities and usage in the space weather enterprise significantly hinders the ability to rank specific missions and new observatories as to their ability to advance priority national capability goals and leads to architecture and gap analyses that are not coordinated with operational agencies to produce optimized improvements in operational capabilities.

The continued siloing of space weather–related subjects ("solar physics," "space physics," and "ionospheric physics," etc.) in higher education and the lack of dedicated space weather departments and degree programs at major research institutions continues to limit the pipeline of systems- and predictive-science expertise required to unify space weather as a legitimate field of research and to advance key capabilities within it.

NOAA NESDIS's traditional approach has been to develop operational missions for weather forecasting and nowcasting only after key technologies have reached a high technology readiness level (TRL) and have been demonstrated on scientific research missions operating in identical or similar orbital locations as that planned for operations. The panel suggests a more streamlined approach (Figure E-8), whereby NOAA can develop operational missions following successful proof-of-concept using OSSEs and OSEs. Such OSSEs and OSEs are, as examples, possible for a Sun–Earth L4 mission OSE using STEREO data or for an OSSE demonstrating how a LEO constellation could provide more impactful thermospheric density products. NASA's Space Weather Program may provide additional pathfinders and allow for the more rapid development of operational assets.

NOAA currently lacks an effective funding mechanism for applied research and predictive model tool development. The tri-agency NASA/NOAA/NSF (now quad-agency with the recent addition of DoD) Space Weather Research to Operations and Operations to Research (R2O2R) program has so far struggled to advance concepts up the readiness level (RL) chain to new operational capabilities.

Space weather research relevant to the exploration of the Moon and Mars in support of the Artemis program is an important priority that the panel believes can be advanced through joint funding with other relevant NASA divisions/directorates—and never solely at the expense of SMD/Heliophysics science mission development or research and analysis (R&A) programs.

The use of proprietary models and data sources in operational space weather forecasting and nowcasting severely hinders progress, supports inefficient silos of expertise, and maintains exclusive and inequitable competitive advantages in grant funding opportunities. All models and most data used in NOAA tropospheric weather forecasting are open source, and mechanisms exist for community contributions to their development, validation, and verification. Space weather needs to follow suit.

The role of the space weather proving grounds in the R2O2R process has not been sufficiently clarified, with the Space Weather R2O2R Framework jointly covering proving grounds and testbeds. While the role of "testbeds" has greater clarity because of its long history of use in the tropospheric weather enterprise, "proving grounds" require further definition to enable the community to understand their purpose and relation to NASA and NSF space weather–related research, and to promote community engagement with proving ground activities.

E.4.2 Strategies

The following strategies center around an overarching objective during the next decade to empower and further develop an agile, networked, and coordinated national space weather enterprise across vested government agencies, academia, and the commercial sector. Developing an improved and orchestrated national space weather enterprise directly addresses SWAG Finding 1, described earlier, and is critical for best achieving the goals defined in the previous section. Along these lines, cross-agency strategies are listed here, and these are followed by strategies that target specific goals, with strategies broken into basic research, applied research, and operational needs.

All of the following strategies are deemed to be essential to ensure progress toward achieving the goals identified by the panel. Note that these are not presented in ranked/priority order and relative importance is not to be construed from their positions in the list.

Strategies to Achieve Critical Goals

Cross-Agency Strategies

The following strategies require coordination between multiple agencies. The panel suggests that the SWORM subcommittee take responsibility in ensuring that the proper coordination is put in place between agencies for these strategies to be implemented.

1. *The panel suggests that SWORM should ensure that space weather OSSEs and OSEs are funded and performed. This is needed to optimize the selection, deployment, and operational use of all new ground- and space-based observing systems used for space weather forecasting and nowcasting*. OSSEs are simulation and modeling experiments that can be used to evaluate the impact of new observing systems on space weather predictive models and operational systems. OSSEs need to be conducted to evaluate new observatory concepts, including technology demonstrations and pathfinders, intended for transition to operational use (e.g., see Figure E-8).

   - OSEs need to be conducted prior to incorporating any new observatory (either space- or ground-based) into an operational space weather system. Many space weather gap analysis exercises and suggestions are fundamentally limited by the inability to quantify how a new measurement or observation will impact the accuracy, lead time, and usability of space weather forecasting (and nowcasting). The panel suggests that SWORM put in place the agreements and suggests funding mechanisms for these OSSEs and OSEs with coordination between the involved agencies.
   - The panel suggests that the development pipeline, including OSSEs and OSEs, be required only for observatories that are being developed explicitly for operational space weather use and not more generally for scientific missions and observatories that might transition to operational use at some point after their prime mission concludes. However, the panel suggests that OSEs still be conducted as proof-of-concept and cost-benefit analysis for any observatory transitioning to operational use. Developing OSEs and OSSEs would have the additional advantage of developing, validating, and testing the infrastructure and data exploitation pipeline for real-time data for space weather forecasting and nowcasting. The panel notes that, for tropospheric weather, both NOAA and NASA have similar and overlapping capabilities in this area.

2. *The panel suggests that space weather–relevant data from NOAA, NASA, USGS, NSF, and DoD/NSS,*[17] *including instrument calibration data, be collected in a centralized portal with professional standards of stewardship (version control and documentation)*. With the suggested development of space weather research missions by NASA and the availability of critical measurements from operational agencies, the volume and type of data available for space weather research are increasing and changing. Documentation and archiving are necessary to enable the space weather research community to participate in the validation and verification of relevant models. This includes ensuring that the data pipelines, documentation, and calibration to use operational data for science are established and enable space weather research. The national space weather enterprise will benefit from the research community having full access to the operational space weather data and forecasts currently being collected or generated by NOAA, NASA, USGS, USAF/USSF, and commercial and international providers through centralized, standardized, and user-oriented data (observed and simulated) repositories.

   - All real-time data, model outputs, and forecasts produced and used for space weather forecasting need to be archived with adequate metadata and supporting information.
   - The panel suggests that DoD/NSS (National Security Space) evaluate their internal relevant data sets and consider how those may be scrubbed of sensitive and/or classified information and details so that some valuable space weather data may be made available.

[17] "National security space (NSS) launches support the military and intelligence community." See Sayler (2023).

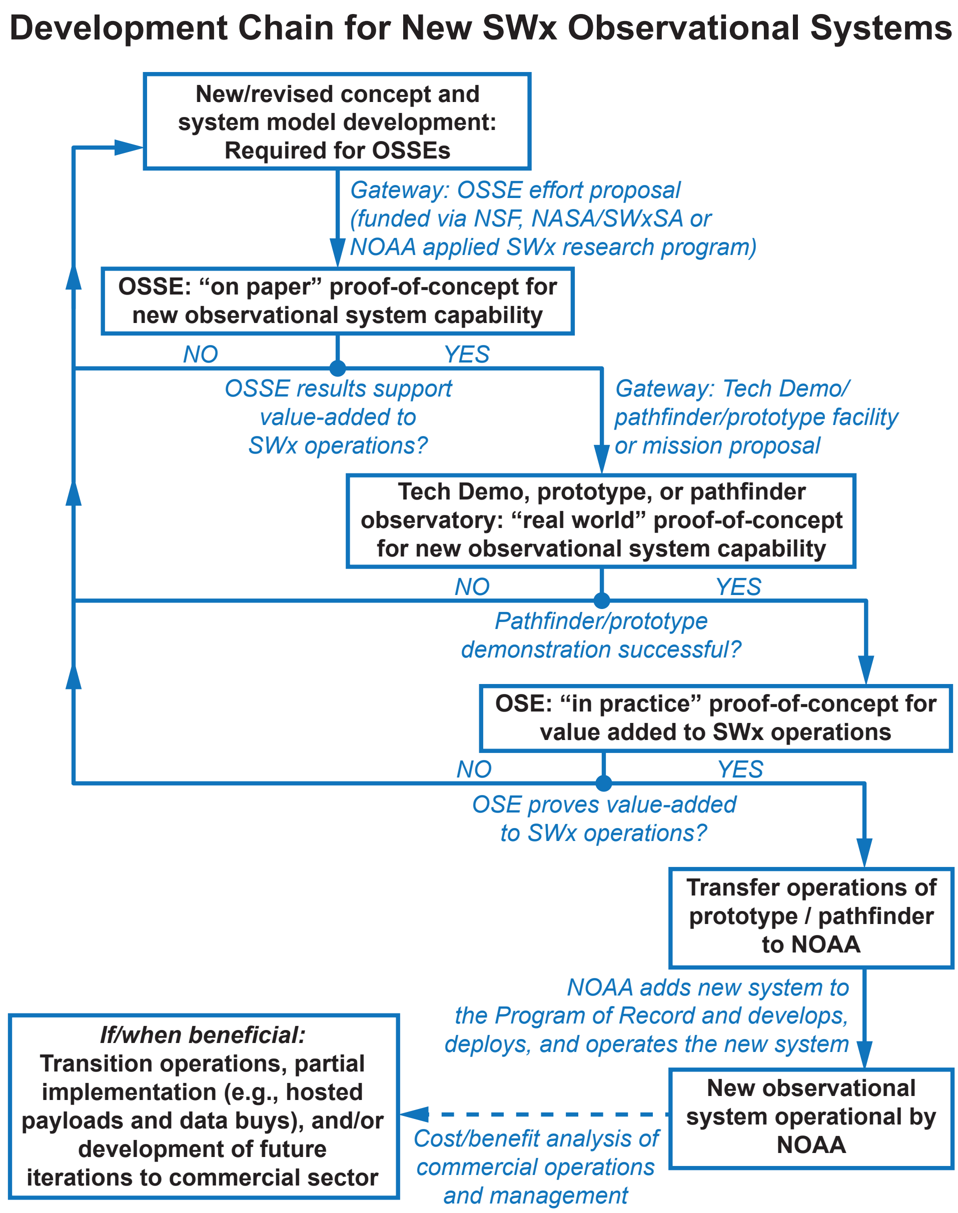

FIGURE E-8 A conceptual strategy for the development, testing, and deployment of new space weather observational systems, both ground-based and space-based. Under this development chain, any concept for a new observational system would complete a series of steps and gateways (from top to bottom in the figure), which march the concept up through the readiness levels for operational use via a series of OSSE, tech demo/prototyping/pathfinder, and OSE proof-of-concept stages.

3. *The panel suggests that relevant agencies coordinate to develop and maintain key space weather observations used in operations*. For example,

   - GONG, and its potential upgrade, ngGONG[18] (next-generation GONG), are to provide pixel velocity, intensity, and magnetic-flux images of the Sun.
   - The Radio Solar Telescope Network (RSTN), and its modernization, are to provide observations of solar radio bursts.
   - The addition of a U.S.-based antenna capable of monitoring solar radio flux at 10.7 cm that has a long track record as a proxy of solar activity.
   - Neutron monitor networks, which provide observations of high-energy particles striking Earth's atmosphere, are needed during ground-level enhancements to assess their intensity and geographic extent.
   - The expansion of ground-based magnetometer networks that measure magnetic field perturbations that can impact the power grid.
   - Ionosondes that provide observations to support nowcasts for HF communication impacts during, for example, post-storm MUF depressions.

4. *The panel suggests that vested agencies and departments continue to establish structure and funding for the space weather testbed to facilitate formal, two-way engagement between the space weather research and operations communities and space weather end users in impacted industries and sectors (in agreement with SWAGF&R23 R.13.1)*. This is required to understand and qualify end users needs and for the development and prioritization of improved space weather applications and operational nowcasting and forecasting products.
5. *The panel suggests that SWORM agencies work to understand the economic impacts and evolving risk to infrastructure from space weather impacts, for the determination and prioritization of new space weather products and services (in accordance with the 2019 National Space Weather Strategy and Action Plan and recommendations in the SWAGF&R23, Chapters 7 and 8)*. In partnership with end users, new space weather benchmarks, scales, and metrics need to be developed (SWAGF&R23, Chapter 6).
6. *The panel suggests that SWORM ensure that the quad-agency Space Weather Research to Operations to Research (R2O2R) program, which is currently managed by NASA, NOAA, NSF, and DoD, is adequately funded*. In addition, the panel suggests that the scope of any R2O2R program focus clearly on the development of forecasting and nowcasting models and/or validation, as well as forensic reconstructions, that are required to meet identified user needs. The panel suggests that both the O2R and R2O portions of the R2O2R program bridge basic and applied research, space weather science, and OSSE and OSE development and testing, and that the development and testing of new, pathfinder observatory systems are adequately funded between the agencies. The panel strongly suggests that any expansion of the R2O2R program at NASA be funded through an augmentation of the NASA Heliophysics budget and *not* at the cost of fewer heliophysics science missions or a reduced R&A budget and portfolio.
7. *The panel suggests that sufficient and sustainable funding schemes are created for the final transition of models and instrumentation/observatories to relevant operational offices with support for validation and training*. In addition, the panel suggests that SWORM ensure that there is a smooth transition as model development moves between agencies and from one RL to another. The panel suggests that funding schemes and memoranda of understanding are put in place for the R2O transition of instrumentation, sensors, or observatories (whether ground-based or space-based), with a clear definition of the roles of instrumentation, science, and operational teams as well as support for continuing calibration and validation. (See Figure E-8 for a conceptual development chain for new operational observatories.)

[18] The National Solar Observatory (NSO), which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation Division of Astronomical Sciences, is "promoting the definition and design of the Next Generation Global Oscillations Network Group (ngGONG)." See "NgGONG—NSO—National Solar Observatory," at https://nso.edu/telescopes/nggong. The entity or entities that would manage ngGONG operations have not been determined. (See the following for suggestions from the Panel on Space Weather Science and Applications.)

8. *The panel suggests that vested agencies and departments expand and sustain space weather research "proving grounds" in government, academic, and commercial environments* (in accordance with SWAGR&F23 R.13.1), and increase the scope and activity of government "testbeds" for validating and transitioning research products to operations.
9. *The panel suggests that space weather–focused programs specifically support the enabling of probabilistic hazard assessment and state prediction across the priority goals*. Uncertainty quantification and probabilistic modeling are key components of providing actionable information to end users. Standard approaches generating probability distributions express uncertainty but may not translate to allow the uncertainty to be used in assessing impacts. Many space weather hazards are driven by spatiotemporally dynamic structures and systems, and the physical domains of space weather exhibit hysteresis in their evolution. In physical domains that are impacted by these considerations, data assimilative and/or ensemble methods using multiple realizations of the hazard environment may be required to appropriately quantify errors and characterize the uncertainty in hazard to the end user.
10. *The panel suggests that agencies involved with space weather develop a dedicated on-orbit communications relay network, standard protocol, and dedicated global ground station network* to enable and allow for very low latency space weather data streams. Currently, reliance on the Deep Space Network is a major bottleneck and barricade, and assets in LEO (and elsewhere near Earth) are often unavailable to provide real-time data streams owing to a lack of space-based relay and/or ground station access. Space weather measurements in the upcoming decades will certainly include remote observations from distant platforms (e.g., but not limited to the Sun–Earth Lagrangian points L4 and L5 and the Sun–Mars Lagrangian L1), as well as from large orbital constellations in Earth and solar orbits. The panel is concerned that existing communication networks and stations will not be sufficient to address future space weather needs and requirements.
11. *The panel suggests that funding agencies encourage and support the establishment of heliophysics departments in major research universities with support for faculty positions in the applied science of space weather*, forecasting/predictive systems research, and data science as well as multidisciplinary solar and space physics research. The current siloed approach and the lack of a unified name for our field of research have produced independent solar, geomagnetic, and ionosphere/thermosphere experts who lack the system- and predictive-science knowledge and skills to significantly advance space weather as a field.
12. *The panel suggests that vested agencies and departments establish and sustain professional workforce development programs in space weather operations and applications development, in agreement with SWAGR&F23 R.13.6*. This will enable professionals in space weather forecasting, engineering development, and policy (i.e., critical workers in space weather outside of the traditional research fields) to increase their knowledge base and improve national preparedness for extreme space weather events.

Structural Suggestions to the NASA Space Weather Program

The panel suggests that the NASA Space Weather Program take the following actions.

1. *Develop a dedicated mission line in the new Space Weather Program called the Space Weather Explorers (SWEx) and include in this line mission of opportunity (MO) flights.*

Missions proposed to the SWEx program could be either space weather research pathfinders for future space weather operational missions or missions taking measurements that close known space weather observational data gaps hindering space weather research. Pathfinders could be in terms of technology demonstrations (e.g., solar sail, propulsion, new observational technology) needed for future space weather platforms, instrumentation (e.g., miniaturized particle instruments), or pathfinding demonstrations (new orbits, new capabilities) to intentionally develop new data sets that can be used for OSEs. Data from such SWEx pathfinders will be useful to transition from OSSEs (i.e., mission concept validation) to OSEs (i.e., new operational observatory validation).

The panel suggests that programs take advantage of rideshare opportunities made possible by ESPA and propulsive-ESPA rings, especially with NOAA (and other) launches to geosynchronous orbit, the Sun–Earth

Lagrangian L1 point, and polar low Earth orbit (LEO), as well as launches associated with the rapid, frequent deployment of new assets into proliferated LEO, the Moon to Mars (M2M) program, and planetary missions to Mars, Venus, Mercury and near Earth objects. For examples of strategic and targeted space weather observational gaps that can be filled with new observatories via the new SWEx mission line, MOs, and/or rideshare opportunities, see Figure E-9(a–c).

The panel strongly suggests that the new Space Weather Program be funded through an augmentation of the NASA Heliophysics budget and not come at the cost of fewer Heliophysics Science Explorers or a reduced research budget and portfolio.

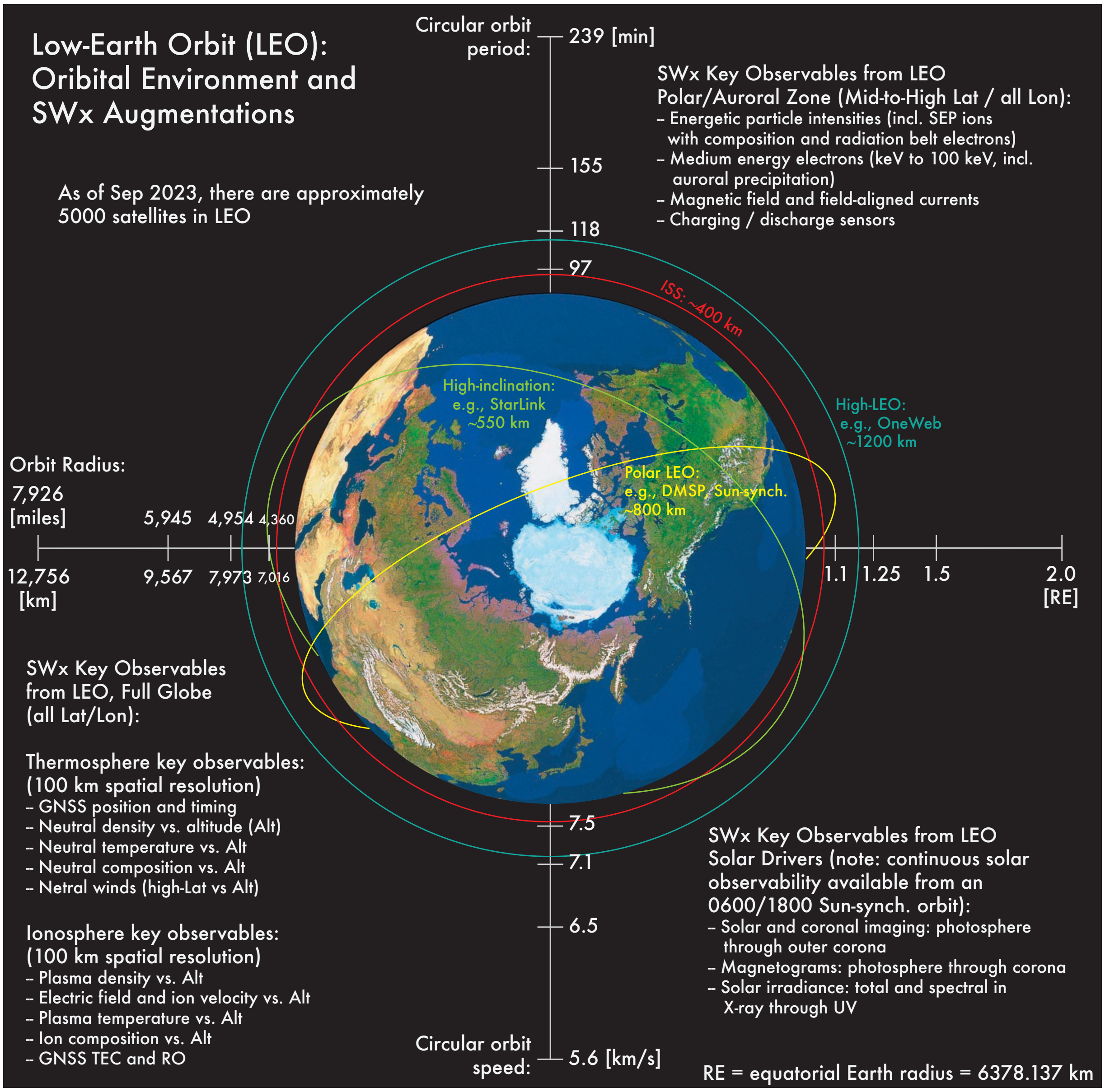

FIGURE E-9a Low Earth orbit (LEO) orbital environment and space weather augmentations.

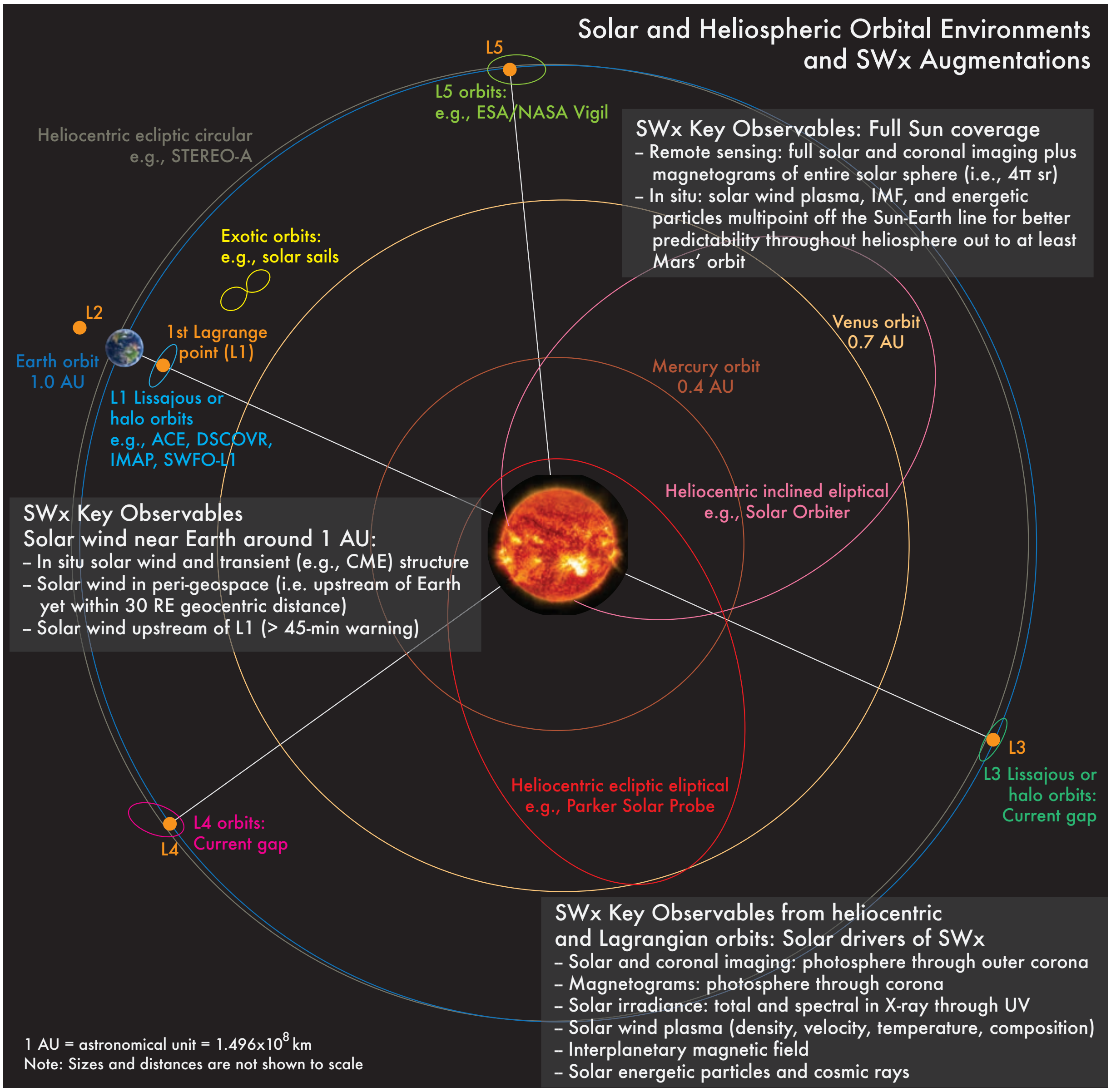

FIGURE E-9b Solar and heliospheric orbital environments and space weather augmentations.
SOURCE: Sun image from NASA.

As with the Heliophysics Science Explorer program, it is suggested that the new SWEx program consist of competed and PI-led spaceflight missions. It is suggested that mission goals are left to the proposing teams but that they map to existing (e.g., the NASA Space Weather Gap Analysis, the LWS Architecture Study, and this decadal survey) and future documented space weather gaps and/or needs.

The following example observations could be achieved via a cooperative national or international mission or as a stand-alone mission under the NASA SWxSA program:

- Global altitude–latitude upper atmospheric neutral densities in LEO (Goal 2).
- Solar wind and interplanetary magnetic field measurements from sunward of the Sun–Earth L1 (Goal 4).

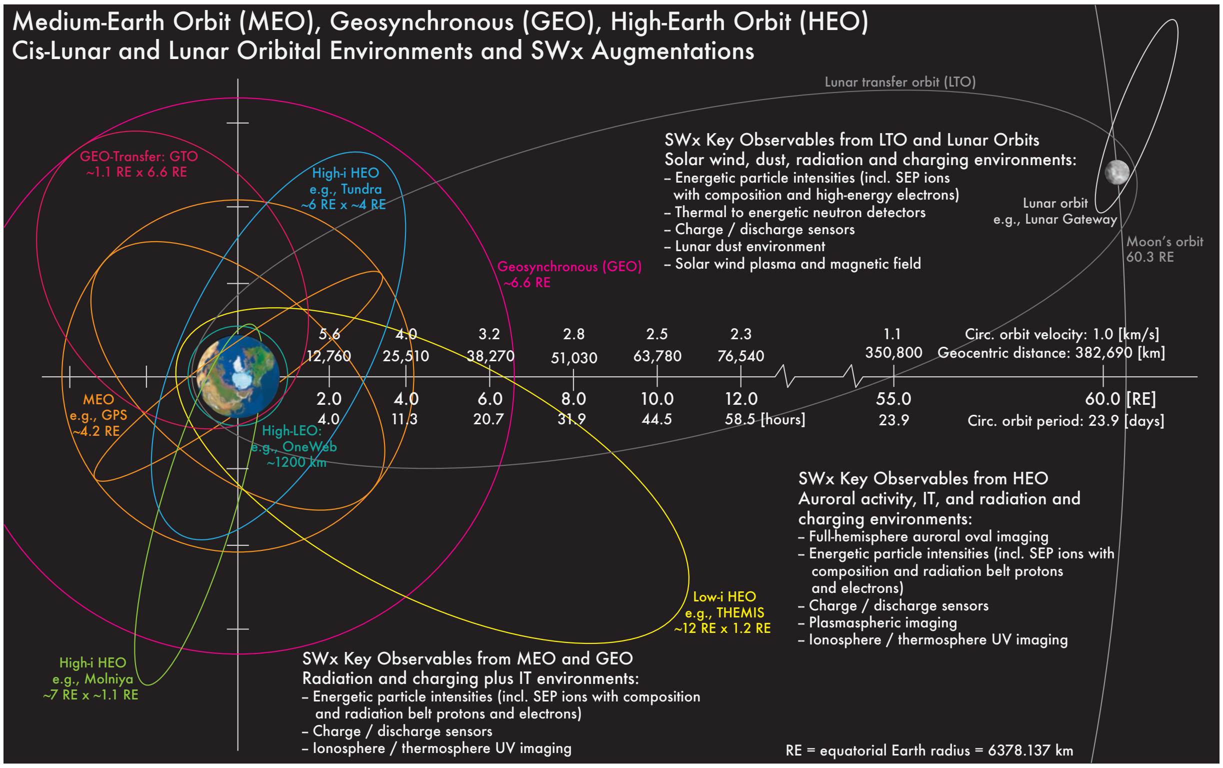

FIGURE E-9c Medium Earth orbit (MEO), geosynchronous equatorial orbit (GEO), high Earth orbit (HEO), cislunar, and lunar orbital environments and space weather augmentations.

- Plasma, energetic particles, and magnetic field measurements from the cislunar magnetotail region (Goal 3).
- Measurements of thermospheric interaction with a drag test object in LEO (Goal 2).
- Dedicated instrument suites for characterization and real-time knowledge of the space weather environment on the lunar surface (Goal 3).
- Other measurements as described in the NASA Space Weather Gap Analysis—for example, solar wind and magnetic field measurements from peri-geospace.

2. *Include a Space Weather Enhancement Option (SWxEO) to the suggested Heliophysics Explorers line, LWS, and STP mission proposals that is reviewed as part of the concept study review (CSR) at the end of Phase A and becomes one of the aspects taken into consideration for down-selection.*

This echoes Recommendation R.10.3 in the SWAGF&R23. The desired multipoint measurements relevant to space weather can be provided by a combination of SWEx and augmentations on science missions through SWxEOs. Augmentation from SWxEOs is best thought of as being based on orbits and observables (measurements, availability of data in real time, etc.) independent of the science objectives of the mission.

3. *Develop global full-Sun science measurements (360-degree longitudinal and polar region coverage) of the solar photosphere and outer atmosphere, with magnetic field, outer atmosphere, and corona imaging and in situ energetic particle measurements.*

Several priority goals (e.g., Goals 1, 3, 4, 5, 6, and 9) would be significantly advanced, both in their research and operational components, by the availability of continuous, simultaneous, intercalibrated, full-Sun measurements that include both equatorial and polar regions. The capability to view all longitudes of the Sun and the polar regions simultaneously will enhance our ability to develop more advanced predictive models of how solar active regions evolve and erupt and advance fundamental research concerning how the polar magnetic field influences the solar wind and dynamo. Given the demonstrated challenges calibrating identical sensors for GONG, the panel feels there is great risk in merely coordinated observations of the solar magnetic field from the equatorial and polar regions. A unified measurement system using identical magnetograph instruments is viewed as the most worthwhile implementation.

4. *Ensure that all models and databases developed and maintained under government funding for space weather research or operations are open source and in user-friendly formats.*

While it is noted that a private entity that funds the development of a model or tool through its own capital has the right to restrict intellectual property rights, government-funded models and tools ought to be the property of the citizens of the United States and need to be freely available, with no restrictions, as open-source software for community use and development. To enable this more dynamic and productive development environment, NASA could, for example, expand the funding and mission mandate of the GSFC/CCMC facility to support non-NASA researchers in accessing and modifying existing codes or databases under controlled conditions, in analogy with the Developmental Testbed Center for numerical weather prediction (NWP) models run by NCAR through NSF, NOAA, and DoD support.

Strategies Specific to NOAA

The panel suggests that NOAA take the following actions.

1. *Establish a dedicated space weather applied research program office within the NOAA OAR division, as recommended by the SWAGF&R23, for implementing the PROSWIFT Act (published April 17, 2023).*

The panel concurs with the SWAGF&R23 recommendation and reiterates the need for a dedicated applied research program at NOAA that would be primarily responsible for applied space weather research, funding of external applied space weather research grants to the academic and commercial sectors, and new operational and applications model development for use in space weather forecasting centers and other operational offices. The new program office would also bolster R2O2R within the national space weather enterprise.

2. *Expand the scope of space weather missions being designed and flown by NESDIS to address the issues noted earlier (see Section E.4.1) and to realize specific goals discussed here.*

In particular, if the required technology is at high TRL and the operational and application capabilities have been demonstrated through previous missions (perhaps at other orbital locations), the panel suggests that NOAA design and fund such space weather operational missions, even if NASA research missions have not been flown in identical orbits. Specific missions could include (in no preferential order; see also Figure E-4(a–c) for additional key space weather observables listed for different orbital regimes):

- A Sun–Earth L4 solar energetic particle and active region monitoring mission (see Goal 1). This mission would enable key energetic particle warning capabilities that are currently lacking. L4 provides a vantage point of the Sun that can track active regions on the solar disk that are most geoeffective from the point of SEP propagation, which is a distinct advantage over observations from along the Sun–Earth line (e.g., Earth-based or at L1). Such an observatory would also support future crewed spaceflight to Mars by providing more comprehensive observations of SEPs and solar activity off the Sun–Earth line. As an L4 mission would provide a new vantage point of the Sun, it is suggested that such a mission include science instruments that address gaps in scientific knowledge with an operational component that allows for public access to measurements in real time.

- A dedicated LEO "calibration satellite" fleet, to enable thermospheric density model assimilation (see Goal 2). Such a fleet is currently tracked by DoD, but its data are not publicly available. As the Department of Commerce stands up a civil space traffic coordination function equivalent to the current DoD capability, it will be imperative to replicate this key space weather measurement capability in an open environment.
- A global, dual-hemisphere auroral imaging mission (see Goal 5). This mission would ideally provide continuous imaging of the entire auroral ovals in far ultraviolet (FUV) for both the northern and southern hemispheres simultaneously. Real-time observations of the full auroral ovals would provide invaluable nowcasting and forecasting capabilities compared to the current state-of-the-art auroral activity model, which is an empirical model using statistical results from archived data sets.

3. *Clarify the role of space weather proving grounds in the R2O transition process.*

To address the concerns noted in Section E.4.1 and to make clear that the wider community will have a role in this new type of facility, NOAA could hold open and transparent public meetings specifically designed to engage the wider community in this new concept.

4. *Increase support for the Space Weather Testbed as a forum for researchers, forecasters, and end user engagement (related to preceding item).*

Furthermore, the panel suggests that NOAA provide, and continuously update, a baseline of current operational model and forecast product performance metrics and skill for the validation of new capabilities in the proving grounds and testbed.

5. *Establish a program in NWS to coordinate and provide long-term support for ground-based (including air- and sea-borne) space weather observations used in space weather operations (in agreement with SWAGF&R23 Recommendations R.6.1, R.6.2, R.6.3).*

Examples of these observations include, among others, the GONG solar magnetogram and H-alpha observing network, the magnetometer network, the Simpson Neutron Monitor Network, and the Continuously Operating Reference Stations (CORS) GNSS receiver network. The panel also suggests that this office lead efforts to develop, expand, optimize, and modernize ground-based space weather observation. These would include, for example, ngGONG and a concept to develop a system of sea buoy–based GNSS receivers. It would also include contributing to the modernization of the DoD Radio Solar Telescope Network (RSTN).

6. *Expand support for commercial data buys for assimilation into space weather forecasting models.*

Provisions for free and open public access to the data, once they are purchased by NOAA, need to be an element of this strategy.

Strategies Specific to NSF

The panel suggests that NSF take the following actions.

1. *Support the design, construction, and operation of ground-based facilities for space weather research that can serve as proving ground for ground-based operational facilities (see also Figure E-8).* In concert with the new NOAA/NWS office discussed earlier in Section E.4.2.1.3, item 5, the NSF would work to increase the availability of space weather–relevant, ground-based observations for research and forecasting.
2. *Expand the Faculty Development in Space Science (FDSS) program to include a Faculty Development in Space Weather (FDSW) program.* This would be a primary source of support to realize the cross-agency strategy described earlier (see Section E.4.2.1.1). FDSW faculty could be based in engineering colleges to ensure cross-fertilization with application-focused instrument and mission development programs.

3. *Expand educational opportunities for space weather–related hardware and research programs (related to preceding item).* Students and early career scientists benefit greatly from CubeSat, summer schools, and faculty development programs run through the NSF.
4. *Encourage and support the development and use of OSSEs to validate new space weather-relevant, ground-based observatories (related to the first item in the preceding subsection) and qualify their potential benefits to operational systems.*

Strategies Specific to Each Priority Goal

The goals are listed in the order in which they appear in the previous chapter—that is, grouped by priority category. See the Summary Table at the end of this section. Under each goal, the strategies are not ranked.

Goal 1: Develop an Accurate and Reliable 12-Hour Lead Time Probabilistic >M1 Solar Eruption Forecast and Associated SEP Event Forecast with 6-Hour Lead Time

Summary of Goal

Solar magnetic eruptions are the root cause phenomenon behind extreme and life-threatening space weather events. Current human-in-the-loop and model forecasts have unrealistically long lead times (up to 72 hours) and low skill at all lead times. To achieve usable forecasts for users across multiple end user groups, reliable solar eruption and SEP forecasts with shortened lead times at or below 12 hours need to be developed.

The strategies to achieve this goal include theory, modeling, and observational efforts to better understand the evolution and eruption potential of active regions, the early stages of formation and growth, and triggering and evolution of coronal mass ejections (CMEs) and CME-driven shocks, and the acceleration and transport of solar energetic particles (SEPs) to various locations in the inner heliosphere.

Basic research needs:

- Continuous high-resolution helioseismic observations of subsurface active region formation, flows, and emergence over the lifetime of specific active regions.
- Chromospheric and coronal vector magnetic field measurements to assess whether magnetic activity in these regions is a more effective predictive indicator of eruption triggering.
- In situ SEP energy, flux, and compositional measurements from multiple locations to ascertain where and how SEP generation takes place in active region reconnection sites and in CME shock-fronts.
- Well-funded R&A programs for fundamental space weather research studies to improve understanding of emerging magnetic flux, coronal and chromospheric magnetic fields, active region eruption potential, coronal mass ejection and shock formation and expansion, and particle acceleration and transport, including magnetic connectivity.
- Photospheric magnetic field measurements of the polar regions (>60° latitude) for improved background solar wind models and polar coronagraphic imaging for CME propagation structure. Additional coronagraphic and magnetogram measurements of coronal connectivity from polar vantage points are expected to enhance knowledge of magnetic connectivity between active regions and topology of the inner heliospheric solar wind, CME propagation, shock structure, and evolution, and hence aid in predicting SEP generation and propagation through the inner heliosphere.

Applied research needs:

- Simultaneous full 360-degree measurements of photospheric magnetic field in the solar mid- to low-latitude regions, coronal imaging, helioseismic flowfields, and coronagraphic structure. This is needed to have measurements of active region structure, evolution, and eruption that can be analyzed to advance eruption prediction and SEP generation.
- Sustained funding for space weather applied research centers dedicated to developing advanced models for predicting solar eruptive events and SEPs. Such centers could be part of a dedicated space weather

research program for data assimilative and/or AI/ML models of active region evolution to eruption and AI/ML techniques for sparse data sets, data-assimilative time profile forecasts, and forecasts for extreme events, with increased accuracy and lead times.
- Development of small and versatile instruments for energetic particle measurements so that they may be readily added as rideshares to other packages and distributed everywhere throughout the heliosphere.
- Development of robust methods for absolute and relative calibration of solar magnetograph instruments.

Operational needs:

- Observations of the western hemisphere of the Sun (e.g., from the Sun–Earth L4 point) for active region and SEP monitoring by the next solar maximum (~2035). A minimal set of measurements would include intensities of energetic particles (electrons, protons, and heavier ions, species resolved) over energies ranging from tens of keV to hundreds of MeV (MeV/nuc for heavier ions), EUV and X-ray measurements of the solar disk, a coronagraph, and a magnetogram to measure active region development not well characterized from observations on the Sun–Earth line. Such observations would also support SEP forecasts for the Earth–Mars transit corridor, in support of the Mars missions planned in NASA's Artemis program (see Long-Term Goal 2).
- Solar photospheric magnetograph and high-energy particle instruments to be included in the next generation of L1 and GEO space weather platforms.
- Real-time availability of all relevant space weather data, including
  - Measurements discussed in the applied research needs.
  - In situ SEP and energetic electron measurements and eruption location and timing information.
  - Ground- and space-based radio measurements of shock formation and particle acceleration signals.
- The development, validation, and transition of flare and SEP forecast models into operations and the establishment of pre-eruptive ensemble modeling capabilities.

Goal 2: Develop Physics-Based, Data-Assimilative, Thermospheric Neutral-Density Models, Including an Integrated Modeling Framework for Predicting Leo Satellite and Debris Trajectories, Capable of Accurate and Reliable Forecasts During Geomagnetic Storms

Summary of Goal

It is not enough to have a two-line element (i.e., Keplerian plus fitted drag) model of the proliferated LEO environment to successfully operate the multiple mega-constellations (i.e., thousands of satellites per constellation) planned for this region of geospace and to ensure that the region remains a viable orbital regime for research, exploration, and commerce in the future. It is necessary to develop a model of how satellites and debris interact with the geospace orbital environment and how these interactions influence orbital trajectories. A critical aspect of improved orbit prediction in LEO is the ability to better model, nowcast, and forecast the thermospheric environment, especially its 3D (i.e., latitude, longitude, and altitude) dynamics during geomagnetic storms. Physics-based models empowered by data assimilation using actual observations from proliferated LEO offer much promise for advancement on this goal. This goal, while not strictly a "space weather" goal, is critically important to accomplish in order to improve our ability to characterize the LEO environment and to create better models and tools for satellite operators and space traffic management coordinators to use in ensuring a safe operating environment in proliferated LEO and the viable usability of LEO in the foreseeable future.

Basic research needs:

- Measurements from GDC as prioritized in the previous solar and space physics decadal survey. Such measurements are critical to understand ionospheric and thermospheric variability, including neutral-density changes during geomagnetic storm periods. Such observables, including several of those to be made by GDC, were also highlighted as critical gaps in the NASA Space Weather Science and Applications Observational Gap Analysis.

- Fundamental investigations of the physics driving the dynamics of the ionosphere and thermosphere. In particular, such research studies need to focus on aspects that would be particularly advantageous to advance with the goal of data-assimilative modeling in mind. The thermosphere is strongly coupled to Earth's ionosphere, which in turn is strongly coupled to the magnetosphere. Magnetospheric physics also directly impact Earth's thermosphere (i.e., auroral processes and energetic particle precipitation). Investigations can focus on either physics-based models that can be stably adjusted using actual observational data (e.g., via a Kalman filter) or the observational data sets required to drive data assimilative models.
- Development of gas–surface interaction physics research, including the development of advanced drag coefficient models for a wide range of satellite geometries, materials, and attitude profiles. This would include (a) characterization of gas–surface interactions and other nonconservative forces in LEO, and (b) laboratory measurements and characterization of gas–surface interactions in orbital environments.
- Development of advanced satellite force models that include drag, radiation pressure, and other nonconservative forces.

Applied research needs:

- Sustained funding for space weather applied research centers dedicated to developing advanced coupled models of the magnetosphere and ITM system along with the required data assimilation models to enable accurate and reliable thermospheric forecasting during geomagnetic storms. These centers would also develop new methods to integrate near-real-time solar spectral irradiance measurements into ITM models and advanced ML approaches to M-I coupling functions and data assimilation improvements.
- Developing instruments and missions as pathfinders for operational follow-ons, as follows:
  - Small-scale accelerometer and mass spectrometer instrumentation for deployment in CubeSat-scale constellation missions.
  - Dedicated rapidly deployable "thermospheric density probes" for near-real-time density data from deployment to reentry into the lower atmosphere during geomagnetic storms.
  - Continuous monitoring of the thermospheric neutral density in LEO across all latitudes.
- Advanced civil ground-based optical telescopes and adaptive optics for LEO satellite and debris tracking research.
- Advanced civil ground-based radar network for characterization of orbital debris down to 1 cm scales.
- Dedicated LEO, MEO, and GEO satellite missions focused on measurement and characterization of orbital debris.

Operational needs:

- Altitude-resolved temperature measurements in the mesosphere–lower thermosphere (MLT) region—that is, pressure altitudes of 20 to ~120 km. Such data are currently being assimilated from the last remaining SSMI scanner on DMSP F17 (launched in 2003) and have been demonstrated as key assimilation sources for coupled whole atmosphere models extending into the upper thermosphere, but there is a need to replace and extend the current measurements for assimilation into NOAA and DoD thermosphere models.
- Development of a dedicated LEO "calibration satellite" constellation for radar tracking data inputs to thermospheric density models (i.e., a civil version of the USSF calibration objects used in HASDM). Such a constellation could be developed with agency support and then transitioned to the commercial sector to generate radar tracking data buys (e.g., see development chain for new operational observatories in Figure E-8). The existing International Laser Ranging Satellite (ILRS) satellites are suboptimal for this purpose owing to their complex surface properties that result in uncertain drag coefficients.
- Research to establish commercial LEO satellite constellation precise orbit determination (POD) data as assimilation sources for operational thermospheric neutral-density forecasting models.
- Advanced satellite orbit propagation and conjunction analysis models with integrated space weather models, customizable visualizations, and scenario testing.

- Integrated thermospheric neutral density, satellite forcing, and orbital propagation models for improved collision assessment and risk mitigation by LEO satellite operators. Note that part of this (thermospheric density model) is the same as the thermospheric density model development portion of this goal.

Goal 3: Characterize and Monitor the Space Weather Environment in Cislunar Space and on the Lunar Surface in Support of the Artemis Program

Summary of Goal

The United States is investing major resources in the NASA Artemis human space flight program, which will see astronauts working on the surface of the Moon in the next decade and eventually setting foot on Mars. To support the Artemis program, it will be imperative to develop the knowledge, measurements, and tools to ensure astronaut safety in these extremely challenging and dynamic environments.

The strategies to achieve this goal address the need for measurements in new environments, improved modeling of the space radiation and charging environments, and new space weather monitoring locations. Distributed particle and radiation measurements are needed throughout the broader heliosphere, in cislunar space, and on the lunar surface to better characterize and model the dynamics of those radiation and charging environments. Improved modeling of the relevant radiation and charging environments is needed to inform human exploration. New space weather monitoring of the Sun's western hemisphere from Earth–Sun L4 would fill existing gaps. Interagency cooperation would facilitate the development of tools and transitioning of forecasting models into operations. Note that several of the suggested strategies under Goal 1 are also relevant and contribute to the strategy of achieving this goal.

Basic research needs:

- The following new observations to characterize the changes in the lunar environment, particularly owing to its orbit with respect to Earth's magnetotail or in response to solar energetic particle events.
  - Particle (neutrons, electrons, ion composition) distribution (thermal to very energetic particle) measurements in different exposed and shielded environments on the lunar surface, including under the regolith and inside lava tubes.
  - Energetic neutron measurements on the lunar surface to better quantify cosmic ray albedo neutrons that are currently estimated through modeling and are potentially a significant source of radiation dose.
  - Energy-resolved measurements of keV to MeV electrons from magnetotail acceleration on the lunar surface (surface charging to penetrating radiation threats), in lunar orbit, and in lunar transfer orbit.
  - Advances in modeling and measurements of the lunar dust environment, in particular how electrostatic and/or dynamic electric fields loft and deposit dust and how dust contributes to the surface charging and discharge hazard to humans, vehicles, and infrastructure.
- Energetic particle measurements distributed throughout the heliosphere on human exploration, heliophysics, and planetary missions to better understand energetic particle production and transport. Such observatories will also support future missions to Mars by providing knowledge of SEP propagation throughout the heliosphere off the Sun–Earth line (considering that Earth-to-Mars transfer orbits are off the Sun–Earth line within the ecliptic plane).

Applied research needs:

- Studies to improve characterizations and predictions of the cislunar radiation environment, including
  - Predictions of solar energetic particle event profiles for consideration in human radiation exposure and SEE mitigation.
  - Effects of variation in the radiation environment on the lunar surface owing to topography and secondaries produced in the regolith.
  - Modeling of the space radiation environment both external and internal to spacecraft (e.g., Gateway) and lunar surface habitats.
- Strategies relevant to Goal 1 on the SEP and eruption measurements and forecasting.

Operational needs:

- A space weather monitor at Earth–Sun L4 with potential instruments to include a magnetograph, coronagraph, heliospheric imager, X-ray monitor, radio spectrograph, EUV imager, energetic particle detectors (electrons, protons, heavy ions), and solar wind plasma and magnetic field instruments capable of supporting forecasts for lunar missions.
- Onboard human and hardware health particle (electrons and ion composition) detectors with wide dynamic range (both intensity and energy, hundreds of keV/nuc up to ≥2 MeV for electrons and ≥1 GeV/nuc for ions) that can make accurate measurements in extreme conditions without saturation in order to properly assess the impacts following strong SEP events without needing to communicate with Mission Control.
- Measurements of energetic ions (protons and heavier ions, species resolved) over energies of hundreds of MeV (MeV/nuc for heavier ions) to GeV/nuc, as mentioned in Goal 1, would help characterize the GCR environment and modulation needed for long-term cislunar (and Mars) mission support as described in Long-Term Goal 2.
- Interagency cooperation to develop tools to support human missions in cislunar space. Along these lines, note here that NOAA has signed an interagency agreement with NASA to collaborate on space weather support for NASA Artemis cislunar and surface missions. The space weather panel suggests that NOAA, in collaboration with NASA,
  - Validate and transition space weather models and applications through the space weather proving grounds and testbed for SWPC operational support of NASA human space exploration—in particular, solar energetic particle forecast models.
  - Develop tools and applications that utilize near-real-time cislunar and lunar surface observations that aid forecast support for NASA human exploration missions.

Goal 4: Develop a 12-Hour Lead Time Forecast of IMF Bz and a 2- to 3-Hour Upwind Nowcast of Other Solar Wind and CME Characteristics at Earth

Summary of Goal

The north–south component of the interplanetary magnetic field of the solar wind and CMEs (so-called Bz) is one of the main determinants of the severity of geomagnetic storms when these structures impact Earth. Forecasting Bz, particularly for fast incoming CMEs, is critical to support a wide range of end users. Current capability in forecasting IMF Bz and solar wind parameters at Earth relies primarily on using solar wind measurements from the L1 Lagrangian point about 1.5 million km sunward of Earth, as well as modeling with nonmagnetized CMEs (i.e., as modeled by ENLIL) using solar magnetograms and coronagraphic observations as main inputs. Making progress on this goal requires an approach over two main fronts: (1) To provide an accurate and reliable probabilistic forecast of Bz with lead times of more than a few hours, remote observations of CMEs combined with numerical models of interplanetary propagation are needed. (2) To provide an upwind 2- to 3-hour short-term forecast or nowcast of the solar wind and IMF that is to impact Earth, upstream measurement of solar wind and CME speed, density, and vector magnetic field at heliocentric distances of 0.9–0.97 AU are needed. Progress will also require understanding the balance between the accuracy and the lead time of the forecasts. Last, to accurately predict the solar wind and IMF conditions that impact Earth's magnetosphere, it is necessary to understand and accurately model how the solar wind and IMF propagates and changes from upstream of L1 to the nose of the bow shock.

Basic research needs:

- Well-funded R&A programs for fundamental space weather research studies to improve heliospheric solar wind and CME modeling and/or propagation techniques, solar wind models with data assimilation and inclusion of subgrid physics to include turbulence and reconnection, and data-driven solar surface and coronal models of CME initiation models with internal magnetic field coupled with large-scale MHD models of solar wind and CME propagation to 1 AU.

- The following new observational capabilities to complement the Heliophysics System Observatory (HSO) for the following observing capabilities:
  - Photospheric and coronal magnetic fields and photospheric vector magnetogram measurements from multiple viewpoints around the Sun, including polar vantage points.
  - Coronagraph and heliospheric imager observations of CMEs from multiple viewpoints around the Earthward hemisphere of the Sun, including polar vantage points.
  - IMF and particle measurements from locations throughout the heliosphere for data assimilation into models.

Applied research needs:

- Sustained funding for space weather applied research centers dedicated to developing advanced models for prediction of solar wind and CME Bz at Earth. Such centers could establish space weather research programs for data assimilation and ensemble modeling techniques for empirical and physics-based codes of CMEs and solar wind.
- Plasma, energetic particles, and magnetic field measurements closer to Earth than L1 (peri-geospace). This is needed to evaluate and understand the accuracy of measurements at L1 and closer to the Sun (i.e., sunward of L1) for predictive magnetospheric models and solar wind-magnetospheric coupling.
- Technology demonstration to raise the TRL of solar sail technology as a means to obtaining more inner heliospheric observations at a variety of locations along the Sun–Earth line.

Either through an operational or through an applied research program, plasma and magnetic field measurements are needed both Sunward and Earthward of L1. Measurements relatively close to L1 (0.95–0.98 AU from the Sun) and Earthward of L1 would be best adapted to an operational program, whereas measurements closer to the Sun would be part of an applied research program or through an augmentation to a basic research space mission. Measurements from ~0.95 AU can improve the lead time to a few hours and make progress toward the goal. Measurements closer to the Sun combined with data assimilation, modeling, and remote observations are needed to reach closure on the goal.

Operational needs:

- Real-time (1) coronagraph images from L1 and at least one more location off the Sun–Earth line (ideally two more locations); (2) radio measurements from the ground; (3) photospheric vector magnetograms from the ground, Earth's vantage point (L1), and one more location east of the Sun–Earth line; (4) extreme ultra-violet measurements from Earth's vantage point and one more location east of the Sun–Earth line; and (5) Heliospheric Imager measurements from at least one location off the Sun–Earth line (ideally two locations).
- Improved operational heliospheric solar wind modeling and/or propagation techniques for CMEs, including their magnetic field, and improved solar wind tracking, tomography algorithms/models, assimilation techniques for remote observations.

Goal 5: Develop Nowcast Capability for Comprehensive Characterization of Auroral Activity, Including Intensity, Boundaries, and Energy Inputs

Summary of Goal

Auroral activity is directly relevant and important to several critical aspects of space weather, including (1) the spacecraft charging and radiation environments in proliferated LEO; (2) the current systems that drive GICs; and (3) ionospheric and thermospheric disturbances and energy inputs that affect communications, navigation, and satellite drag. Currently, operational models of auroral activity are limited to empirical models driven by statistics of historical data sets, and there are no simultaneous, continuous, comprehensive observations of auroral activity in both northern and southern hemispheres. In addition, auroral activity is of high interest to the general public and is a proven pathway for bolstering public support and even citizen science of space weather.

Basic research needs:

- Support utilization of an augment to the HSO that allows for simultaneous observations of multispectral auroral imaging from the ground and space alongside suprathermal to energetic particle measurements from LEO.

Applied research needs:

- FUV and energetic particle augmentations (see Annex E.B) to candidate missions that would support (at least in part) observational objectives required to achieve Goal 5.
- Sustained funding for space weather applied research centers dedicated to developing advanced models for auroral activity and its effects on the ionosphere–thermosphere systems and satellites in LEO. Such centers could be responsible for the development of advanced, probabilistic models of auroral that meet the needs of vested end user communities and support the development of modeling approaches that refine resolution to capture mesoscales in global auroral predictive models.
- Development of next-generation ground-based auroral observing technologies.
- Continued observation of polar cap potential via technologies such as SuperDARN.
- Observations of Field Aligned Current patterns through approaches like Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE).

Operational needs:

- Deploy a set of space-based observatories providing real-time, comprehensive (i.e., full oval) observations of the auroral ovals in both the northern and southern hemispheres, simultaneously and continuously. Note that FUV wavelengths are nominal for such observations because those can be made in both sunlit and dark hemispheres.

Goal 6: Develop Reliable Probabilistic All Clear Forecasts with Multiday Lead Time

Summary of Goal

An All Clear forecast indicates that the space weather environment will be quiet, clear, or nonthreatening for a predetermined duration (e.g., 12 or 24 hours). An All Clear forecast may indicate that a driver, such as a solar eruption or the arrival of a CME, will not occur. Alternatively, an All Clear forecast may indicate that an impact, such as a geomagnetic storm or increased atmospheric drag, will not occur. All Clear will have different definitions for different phenomena and end users and would be developed independently for each need. End users would benefit broadly from accurate and reliable probabilistic forecasts that given phenomena will not occur, or will come to an end, in a specific timeframe at a specific location.

The strategies to advance All Clear forecasting include improved knowledge of the physical processes that drive eruptions and subsequent variability of the conditions in the heliosphere and geospace environment (including cislunar space, magnetosphere, ionosphere, thermosphere, and ground/GICs environments). These strategies additionally support Long-Term Goals 1 and 2.

Basic research needs:

- Studies and modeling of the physical processes that drive space weather, including the physical processes that drive solar eruptions, propagation of structures and particles in the heliosphere, arrival of structures and particles at Earth and corresponding impacts in the magnetosphere–ionosphere–atmosphere system-of-systems and on the ground.
- Full-Sun, including polar regions, observations as noted in Goal 1.

Applied research needs:

- Identification of the key parameters and observables that allow for reliable All Clear forecasts. Development of models relevant to the All Clear state of the space weather environment and conditions that result in the transition from All Clear to Not Clear states. The space weather panel encourages multiagency cooperation to address these needs.
- Multiday All Clear operational forecast models for the current R, S, and G space weather scales with a plan for expansion to meet new and evolving user forecast needs.
- Full 360-degree longitudinal observations of the Sun as noted in Goal 1.

Operational needs:

- Continuous monitoring of the state of the Sun and geospace space weather environment to allow for the identification and complete sampling of All Clear/Not Clear periods and build up statistics for the development and training of prediction models.
  - Solar driver observations that are relevant to the prediction of the All Clear status of space weather, including chromospheric and coronal vector magnetic field measurements (magnitude, topology, and dynamics); coronagraphic and heliospheric imagers observations of CMEs from multiple vantage points, including off the Sun–Earth line; ground- and space-based radio measurements of signatures of shock formation and particle acceleration; and in situ SEP acceleration measurements from multiple locations.
  - Advanced solar wind monitors (i.e., Sunward of L1 or ahead in the Parker spiral); see Goal 3 on IMF Bz and advanced solar wind forecasting earlier.
  - Comprehensive, low-latency environmental monitors throughout the geospace system-of-systems for all relevant internal drivers plus radiation, magnetospheric, ionospheric, thermospheric, atmospheric (e.g., secondary radiation at aviation altitudes), and ground/GIC observables. See the NASA Gap Analysis for lists of highest-priority observables needed for each region and corresponding space weather hazard/effect.
- Ground-based solar and radio observatories that enable the early detection of solar activity (radio bursts, Mauna Loa coronagraphs) and active region (ngGONG, Daniel K. Inouye Solar Telescope).

Goal 7: Develop Reliable Probabilistic Forecasting (1 Hour) of the Geoelectric Fields with Increased Spatial Resolution (200 Kilometers)

Summary of Goal

The geoelectric field is an important driver of impacts to long conducting infrastructure (e.g., power transmission systems, railways) at Earth's surface. Currents induced in power transmission systems can lead to reduced lifespan, or failure, of transformers and voltage instability and collapse of the network on regional scales. Current capabilities do not address operator forecast needs. Relevant nowcast and forecast capabilities need increased spatial resolution to better characterize regional impacts for operators, and probabilistic forecasting is required to ensure that the models are reliable and actionable from an end user standpoint. The strategies to achieve the goal include new research and operational observations and research and operational model development. In addition to the specific strategy for this goal, advances in capability will be supported by progress toward Goal 2.

Basic research needs:

- Fund space weather research programs for probabilistic spatiotemporal modeling methods and their application to auroral current systems, geomagnetic disturbances, and solar wind drivers for geospace modeling.
- Develop and fund R&A programs for fundamental space weather research studies to characterize and quantify telluric currents and their contributions to magnetic perturbations, auroral drivers of meso- and small-scale current systems that drive geomagnetic disturbances, and the necessary and sufficient conditions for substorm onset and the predictability of substorms.

- Support and provide spatially dense magnetometer observatories at middle latitudes to characterize the spatiotemporal geomagnetic disturbances driving geoelectric field and enable validation of predictive models.
- Support for sustained development of coupled models of the geospace environment through R&A programs for fundamental space weather research studies and applied research centers. These centers would also develop new methods to provide reliable probabilities and multiple realizations of higher-dimensional predictions, incorporating new approaches in data science and data assimilation to accelerate improvements in skill.
- Fund space weather research programs for quantifying event likelihood and hazard impacts for geoelectric hazard.
- Support for modeling work to develop, and validate, probabilistic models of geoelectric field at regional scales and tools producing multiple realizations of spatiotemporal geoelectric field.
- Fund science missions to observe and resolve direct connections between in situ magnetospheric activity and structures and auroral activity and features, providing a pathway to using auroral imaging in hazard zone predictions and resolving the phenomena driving the mesoscale current systems responsible for intense geoelectric fields.

Applied research needs:

- Operations support for probabilistic forecast models of geoelectric field and other tools developed in tandem with power transmission end users.
- Completion of the magnetotelluric survey of the United States and full characterization of the uncertainties associated with the transfer functions. International collaboration to complete a similar survey north of the United States–Canada border would significantly augment the value of the U.S. survey.
- Following open science best practices, the coordinated gathering, dissemination, and archiving of GIC, magnetic disturbance, and geoelectric field measurements.
- Support and provide geoelectric field measurements for model development and validation.

Operational needs:

- Increased spatial resolution magnetometer observations to characterize, at regional scales, the spatiotemporal geomagnetic disturbances driving geoelectric field at midlatitudes, improve nowcasting, and enable validation of predictive models.

Goal 8: Develop a Reliable Probabilistic Forecast of Surface Charging (3 Days), Internal Charging (28 Days), Single-Event Effects (SEE; 6 Hours), and Event Total Dose (1 Day)

Summary of Goal

Satellite and launch operations are affected by several energetic charged particle hazards. Forecasts at the specified timetables are believed to be achievable within 10 years, and initial versions with shorter lead time or lower accuracy are already used today in operations. However, generally operators report that they can improve their operations with longer lead time and more accurate forecasts. The strategies to achieve the goal include new research and operational observations, research and operational, research and operational model development, and decision aid development.

Basic research needs:

- Fundamental science modeling of upstream drivers (CMEs, SEPs, high-speed streams) and magnetospheric particle populations (hot electron plasma, radiation belt particles, geomagnetic cutoffs).
- Additional scientific observations of hot electron plasmas and geomagnetic cutoffs (with energy, species, and angular resolution).
- Supporting data sets to contribute to the physical processes governing the hazardous particle populations—for example, ULF and VLF waves and DC fields.

Applied research needs:

- Real-time solar eruption monitoring and the consequent SEP and CME modeling to support all forecast aspects of this goal (see Goal 1).
- Real-time radiation belt modeling to meet the 28-day internal charging forecast lead time.
- Real-time hot electron plasma modeling in the magnetosphere: ring current, plasma sheet, and aurora, to achieve the surface charging forecast.
- Geomagnetic cutoff forecasts needed to achieve a 6-hour SEE forecast.
- Flight observations of vehicle charging itself to improve models that assess charging risk given a forecast environment. Many of these observations can be obtained opportunistically from missions for which they complement or supplement the science—for example, through existing or hosted payloads.
- Targeted missions specifically to study charging and radiation effects. An example of one such mission would study Spacecraft Charging At High Altitudes (SCATHA for LEO).
- Long-term observations whenever possible to enable probabilistic and AI/ML models.
- All the scientific observations noted elsewhere to improve forecasts of solar eruptions and their interplanetary consequences (CMEs and SEPs).
- Development of real-time data assimilative models of the radiation belts, ring current, plasma sheet, aurora, and geomagnetic cutoffs.
- Tools that can evaluate the environment at a satellite/vehicle location or along its trajectory, often by projecting from the natural coordinates of a model to the physical coordinates of the satellite/vehicle.
- Decision aids that translate these localized environments into likely impacts on satellites and vehicles.
- Decision aids needed specifically for launch, given that the launch trajectory slips forward in time when the launch is held.

Operational needs:

- Continuing real-time upstream solar wind monitoring.
- Operationalizing improved interplanetary input forecasts (CMEs, SEPs, high-speed solar wind).
- Operationalizing the models and decision aids developed earlier.

Goal 9: Develop an Accurate 6-Month to 1-Year (to Within ±20 Percent) Forecast of the Solar Activity Cycle

Summary of Goal

Predicting the characteristics of the solar cycle is important for mission planning and engineering. Current predictive capabilities are hampered by limited understanding of the solar polar magnetic field and surface and subsurface flows that are believed to play a key role in the dynamo generation of magnetic flux in each cycle. Improved solar cycle prediction would benefit a wide variety of end users and activities, including spacecraft designers, mission planning involving long-duration human spaceflight, and managing/planning safe spacecraft reentry.

The strategies to accomplish this goal focus on gaining a better understanding of surface and subsurface solar flows, solar magnetic field evolution, new and improved modeling approaches, and monitoring of the Sun to ensure the continuation of long-term measurements.

Basic research needs:

- Measurements of solar polar magnetic field vector direction, surface and subsurface flows, and total magnetic flux. This is met by full-Sun, including polar regions, observations as noted in Goal 1.
- Research to further the understanding of the solar dynamo, solar flux transport, and evolution of subsurface magnetic fields.

Applied research needs:

- Funding and programs for the implementation of data assimilation techniques to drive solar dynamo models.

- Modeling efforts, including AI/ML, connecting dynamo and/or flux transport processes to specific solar activity.
- Research to evaluate how well sunspot number and F10.7 reflect (i.e., are proxies for) actual solar activity relevant to space weather hazards.

Operational needs:

- Continued long-term measurements to enable a continuous record of solar activity over multiple solar cycles—in particular, sunspot number, F10.7, full-disk magnetograms.
- Establish use of EUV imagery for solar cycle predictive capability as an improved (i.e., higher information content) and alternative method to the traditional use of F10.7cm radio flux.
- Establish a U.S. national capability to obtain continued measurements of the ground-based F10.7cm radio flux as a proxy for solar EUV irradiance over the solar cycle. This provides ongoing continuity with long-term, historical F10.7cm data sets, while also ensuring sufficient data coverage overlap to establish statistical relationships between measured EUV imagery and corresponding F10.7cm radio flux.

Goal 10: Develop a Robust Reanalysis Capability for Forecast/Nowcast Models with Established Community Standard Input Data Sets for All Key Space Weather Drivers and Impacts

Summary of Goal

Reanalysis refers to the process of creating a long-term reconstruction of the state space in the space weather environment. End users employ reanalysis to refine data from the past that determine either specific conditions during a past or ongoing mission or to establish cumulative and worst-case transient design environments. Standard state space models are needed for all key space weather drivers and impacts—in particular, of the magnetosphere and the ITM system spanning many solar cycles.

The strategies to accomplish this goal focus on developing a more robust system for space weather data products dissemination, better collaboration between the agencies, and a complete set of ground- and space-based observations with their proper archives available for the research and operational communities.

Basic research needs:

- The development of (1) robust, detailed, and open-archived version-controlled historical data sets to drive data assimilative models; and (2) new data assimilative models across all relevant space weather domains.
- Partnerships with international agencies to share the technical load for establishing trusted data sets for use in data assimilation and developing the long-term, data-assimilative simulation models.
- Development of numerical simulations that can run for 1+ solar cycles in reasonable timeframes.
- Extension of numerical simulations to cover the entire geophysical domain relevant to technological systems (e.g., add LEO to global radiation belt and plasma models).

Applied research needs:

- Establishment of a clearinghouse for massive data sets from full solar cycle model runs.
- Development of standard file formats and extraction/projection software to map from model grids to real locations.
- Continued long-term, ground-based observations.

Operational needs:

- Continued long-term, space-based observations in GEO, MEO, and LEO and upstream solar wind monitoring.

- Enhanced metadata standards to include information regarding, for example, the timing of observational availability to models and forecasts as it happened in real time and the status of primary and secondary satellites that were used to make the forecast.
- Archiving and public dissemination of operational model outputs for scientific model validation by the research community.

Goal 11: Develop 30-Minute to 1-Hour Lead Time Forecasts of Transionospheric and Skywave Mode HF Radio Wave Signal Impacts (Such as Ionospheric Scintillation, Absorption) in Polar, Midlatitude, and Equatorial Regions

Summary of Goal

The strategies to accomplish this goal focus on enhancing the data available (space and ground) for assimilative models, supporting new and improved modeling approaches for nowcasting and forecasting, and coordinating and supporting ground-based observations as integral to the real-time data ecosystem.

Basic research needs:

- Fund fundamental space weather research studies to improve understanding of ionospheric electron density structuring, drivers and associated impacts on specific users (includes coordinating to obtain appropriate impact data—e.g., OTHR radar data).
- Fund model development for characterization and validation of 3D, time-evolving ionospheric electron density, and if appropriate, including coupling to other regions (e.g., magnetospheric models) to resolve spatial and temporal structures of relevance.
- Fund model development of auroral transport and ionospheric models to enable understanding of particle precipitation effects on ionospheric structure and GNSS signal propagation in the polar ionosphere.

Applied research needs:

- Fund augmentations of LEO and MEO science and commercial missions with GNSS RO instrumentation, enhancing the number of RO profiles/day. For these missions, consider possibilities to reduce data latency in mission optimization. See also this panel's suggestions for related augmentations to missions that underwent the technical, risk, and cost evaluation (TRACE) process (see Appendix G).
- Fund space weather research to develop probabilistic models of electron density impacts associated with different drivers (flares, substorms, etc.).
- Coordinated effort to align NSF and NOAA funding opportunities for advancement in ground-based observational capacity and user needs specifications.
- Lower the barrier of usage for GNSS ocean-buoy network data, and expand the network to optimize coverage for data-assimilative models.
- Engage end users and define appropriate modeling targets and outputs. Work with end users to make data available to space weather research for development of impact-specific models and forecasts.
- Develop forecast tools capable of predictions of electron density structures and associated user impacts in different regions (high-latitude, midlatitude, etc.).
- Continue support for ground-based GNSS instrumentation program (low-cost and scintillation receivers). Fund dedicated activities to enhance real-time data recovery and low-latency enhanced data products (i.e., GNSS TEC with bias determination and removal) to support operational use of systems.

Operational needs:

- Coordinate the development of a comprehensive global network of GNSS TEC measurements with common data interfaces and real-time data availability.
- Coordinate ocean-buoy network optimization and associated data pipelines.

Goal 12: Develop an Accurate and Reliable Aviation Radiation Nowcast and Forecast for Airline Operators During Large Solar Energetic Particle Events

Summary of Goal

Radiation penetration to airline altitudes during major SEP events is a potentially significant hazard to airline passengers and crew. This hazard is particularly acute for the polar route flights that traverse areas of low magnetic rigidity, enabling deep penetration of energetic protons into the stratosphere. The development of an accurate forecast and timely nowcast capability for the environments relevant to aircraft altitudes and radiation exposure is considered a major goal of space weather research.

There is a growing demand from the airline industry for more accurate and reliable aviation radiation forecasts. The strategies to accomplish this goal focus on improved modeling of the atmospheric radiation environment which requires better characterizations of the geomagnetic field and better understanding of particle precipitation into the atmosphere from GCR, SEP, and radiation belts. There is an emphasis on improved measurement campaigns for model development and validation, as well as better observations to support operations. To advance models from a nowcast to a forecast, there is a focus on improving SEP forecasts.

Basic research needs:

- Improved models that transport ionizing radiation through the heliosphere, Earth's magnetosphere, the neutral atmosphere, and aircraft shielding to predict, and provide uncertainties of, human radiation exposure and SEEs in electronic systems.
- Fund research studies that improve characterizations of the geomagnetic field and corresponding energetic particle access to the atmosphere, including the development and launch of instruments to collect low-latency particle data (with energy, species, and angular resolution) from LEO with sufficient density to facilitate data-driven cutoff models.
- Fund research studies to improve forecasts of SEP characterizations (timing, intensity, spectra) in order to advance aviation radiation modeling from nowcasts to forecasts and provide users with actionable lead times.
- Fund research studies that improve understanding of radiation belt trapped particle precipitation into the atmosphere and impact on atmospheric radiation environment.

Applied research needs:

- Fund an OSE to determine the optimal configuration of the ground-based neutron monitor network needed to support operational aviation radiation models.
- Airborne observation campaigns aboard balloons, planes, and drones to increase measurements of linear energy transfer (LET) spectra and total ionizing dose in the atmosphere to understand the steady state atmospheric ionizing radiation environment (SSAIRE), particularly during SEPs, to improve and validate aviation radiation models. The panel suggests
  - Funding the development of a dedicated platform/vehicle needed for 24/7, real-time monitoring of the aviation radiation environment.
  - Funding the development of an on-demand, quick-launch network of platforms that could launch with early warning of an SEP.
  - Work with international partners to develop a global network of airborne radiation measurements for the development of data-assimilative aviation radiation models.
- Investigation into new and alternative air shower measurement techniques—for example, compact neutron monitors, water Cherenkov scintillation detectors—for improved SEP energy and composition analysis.

Operational needs:

- Rapidly deployable aerial radiation measurement platforms to autonomously patrol high-latitude, high-altitude, commercial aviation routes (e.g., the North Atlantic and transpolar routes) during major multiday SEP events.

- Ensure that all relevant observations are available in real-time, including
  - Measurements from the ground-based neutron monitor network used to monitor the background GCR and characterize the high-energy component of solar energetic particle spectra.
  - Direct measurements of the relevant, incident energetic particle populations precipitating into the atmosphere (e.g., high-energy proton and alpha measurements from the GOES spacecraft), including the development and launch of an instrument with >500 MeV differential particle flux observing capabilities.
- Enable development, validation, and transition into operations for a real-time nowcast and forecast model of geomagnetic cutoffs and intensities for all relevant particle species and energy ranges.

E.5 LONG-TERM GOALS AND STRATEGIES

E.5.1 Long-Term Goal 1: Establish an Interconnected System of Observatories, Data Pathways, and Applied Research and Modeling Centers

An interconnected space weather system—for example, the Space Weather Aggregated Network of Systems (SWANS) detailed in the community input paper by Vourlidas et al. (2022)—is essential to serve society's space weather needs by developing and networking an aggregated system of in situ and remote sensing observatories, both space-based and ground-based, and state-of-the-art modeling facilities and centers that will provide space weather end users with accurate, on-demand resources to predict the consequences of space weather on systems distributed on and around Earth and throughout the solar system. Faced with a complex and highly nonlinear system, the strategy is to approach space weather as a "system-of-systems." This allows for the treatment of the space weather problem as a chain of smaller interconnected systems with a research infrastructure plan developed around each of them.

Current space weather observatories, data sources, and modeling capabilities are managed as completely separate assets by independent institutions, teams, and even individuals. In the long term, this is neither a sustainable nor an efficient model for addressing space weather needs. Societal demand for improved space weather evaluation and prediction models is ever-growing as humanity becomes more and more reliant on space-based technology and strives to explore our solar system. Whereas interoperability and data sharing are nice to have in the pursuit of scientific understanding, they are essential for space weather, which often confronts very short timelines to support society in response to a new space weather challenge. For example, SpaceX resumed launch operations only 3 weeks after losing dozens of vehicles in a February 2022 SpaceX anomaly that was attributed to space weather. The infrastructure needs to be in place before the problem arises, because operations cannot be put on hold for extended periods while infrastructure is built. Each piece of the space weather chain needs to be developed and implemented as part of a greater framework. A system-of-systems approach will better empower next-generation space weather capabilities.

Key aspects of such an interconnected space weather system include the following:

- Close collaboration and partnership with the commercial sector.
- Simple, streamlined observatory design and operations.
- Rapid deployment and scalability.
- Establishment of a dedicated, real-time, global communications network enabling very low latency data streams from both ground-based and space-based observatories.
- Data analytics, including ML and advanced data-mining approaches to handle data products from a large, distributed network of observatories.
- Streamlined and accessible data pipelines, cloud computing, and advanced data-ingestive and data-assimilative modeling forming the core components of an interconnected and accessible data system and corresponding centers.
- Strong modeling component leveraging both data-augmented, physics-based models and purely data-driven models.
- Community-wide participation.

Build a Resilient Infrastructure for the Real-Time Dissemination of Space Weather Products for Operations, Research, and Development

A resilient infrastructure spans the chain from the collection and transmission of real-time measurements to the generation of analysis and forecast products to the dissemination of those products to operational and research institutions.

- To ensure that operational measurements are robust and readily available in real time, it is important to develop and implement a dedicated on-orbit communications relay network (and standard protocol) and global fail-safe ground station network to ensure uninterrupted operational space weather data streams.
- The development and maintenance of a centralized control and data-handling protocol for a multitude of ground- and space-based space weather observing systems is needed to facilitate the ingestion, processing, and robust archiving of observational data. (See, for example, DoD's Unified Data Library.[19])
- Infrastructure to process observations and end user products through a low-latency data processing pipeline via a network of dedicated data centers and distributed through open cloud-based data computing systems with readily available processing/analysis tools and the capability for researchers and end users to analyze the data in place.
- Individual space weather observation programs that include a "data integration" component in their project data management plan to ensure that their data can readily and efficiently be integrated into the larger system of systems.
- While many science missions and agencies have as a matter of policy a requirement to share data in a timely manner (following EO 13642; see White House 2013), there remain a few programs that receive U.S. government funding who embargo their space environment data for no discernable national benefit. The panel encourages agencies to end this unhelpful practice.

Enable Scientific Advancements and the Development of Tailored Products in Academia and Industry

- Public access to centralized data centers, as described in Section 6.1.1, is needed to empower academic research and the development of space weather products, through academic and commercial avenues, that complement government capabilities.
- Work facilitated by these data centers would be supported through targeted R2O funding for the development of tools up to high readiness levels and their transitioning into operations.
- The creation of new forums to promote and expedite communication between space weather scientists in academia and industry with government and commercial end users to streamline the development of space weather products and decision support tools tailored to end user needs. Examples of such forums may include digital knowledge bases or a centralized web service to connect key points of contact across the space weather field. In-person forums include conferences dedicated to supporting the R2O chain and simulated space weather exercises involving researchers, operators, and end users.

Enable Timely Instrument Technology Development to Support Future Operational Space Weather Requirements

NASA's current concept of a heliophysics "instrument pantry,"[20] consisting of flight-ready, science-grade, instrumentation available "on the shelf" for rapid deployment as hosted payloads and rideshare MOs, is consistent with what would be required to enable rapid development and deployment of new space weather observatories.

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[19] Unified Data Library Storefront, https://unifieddatalibrary.com/storefront/#/login?returnUrl=%2F.

[20] The term "instrument pantry" was coined by Nicola Fox during her tenure as director of NASA's Heliophysics Division. Mention of the concept appears in a presentation made by the co-chairs of the National Academies' Committee on Solar and Space Physics, at https://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_189684.pdf. A lengthier description of its utility for space weather appears in the minutes of the inaugural meeting of the NASA Space Weather Council on March 2, 2022, at https://smd-cms.nasa.gov/wp-content/uploads/2023/05/SWCMarch22022MinutesasAdopted.docx.

Also needed are expanded funding opportunities for new instrument technology research and development and low-cost flight opportunities for access to space under existing program lines (e.g., HTIDES, LCAS, HFORT) and the new NASA SWxSA program. NOAA might also consider dedicated funding opportunities for instrument development and "pantry" filling. Efforts dedicated toward developing instrument interface (including, mechanical, electrical, digital) standards and requirements would reduce the burden (cost and schedule) of having to redesign or customize interfaces for each particular flight opportunity.

Vision for Organization and Implementation

Figure E-10 shows a more detailed evolution of the network-of-systems over the next 15+ years. The emphasis is on making key technological and infrastructure investments early that allow for multipoint observatories to be developed and then observatories or the technology behind them to be transitioned into operations.

Related Priority Goals and Strategies

Nearly all of the cross-agency strategies highlighted in the Strategy portion of this report describe advancements that are relevant to achieving Long-Term Goal 1. In the coming decade, each strategy could be implemented with foresight, treating it as an individual component that will ultimately be a part of a broader interconnected system-of-systems. Working purposefully toward this long-term vision over the next decade will facilitate the establishment of streamlined and robust space weather capabilities in the following decade.

Most of the *priority* goals and their strategies are directly analogous or closely related to Long-Term Goal 1, in particular the following.

Goal 2: Develop physics-based, data-assimilative, thermospheric neutral-density models, including an integrated modeling framework for predicting LEO satellite and debris trajectories, capable of accurate and reliable forecasts during geomagnetic storms. This goal highlights the need for an accurate satellite drag and debris trajectory modeling system. To accomplish this goal, a complete space weather chain must be in place to robustly collect real-time observational data, process it quickly, and proficiently distribute the results to end users through tailored products. All components of the system-of-systems approach are engaged, providing an opportunity to develop this framework with Long-Term Goal 1 in mind.

Many of the other priority goals involve development of new observational and/or modeling capabilities pertaining to particular space weather drivers or impacts. These disparate yet interrelated goals emphasize the need for an orchestrated systems-of-systems approach. Many of the new developments for the priority goals can be achieved through efforts conducted in parallel with one another; however, because collectively they are all of interest to the entire space weather community, those efforts and their final products should not exist alone and independent of the others. Solutions to some challenges, particularly those calling for new observatory capabilities, can be implemented to deliver on the needs of multiple goals simultaneously, particularly when a new observatory can satisfy multiple goals' observational requirements from a well-designed, strategic orbital or ground-based location(s). Ultimately, the deployment, operations, and data services for a future aggregated network of space weather observatories and data and modeling centers would be most effective if orchestrated with a strategic, versus ad hoc, implementation.

Goal 10: Develop a robust reanalysis capability for forecast/nowcast models with established community standard input data sets for all key space weather drivers and impacts. The goal to develop a robust reanalysis workflow underscores the need for publicly accessible, standardized data sets. The strategies to achieve this goal include creating a clearinghouse for massive data sets, the standardization of data sets, enhanced metadata, the development of software to interact with those data sets, and improved schemes for archiving and dissemination to the public. Implementing these strategies over the next decade in a purposeful manner to address this priority goal may provide a small-scale example of standardization for key components within the broader aggregated system-of-systems.

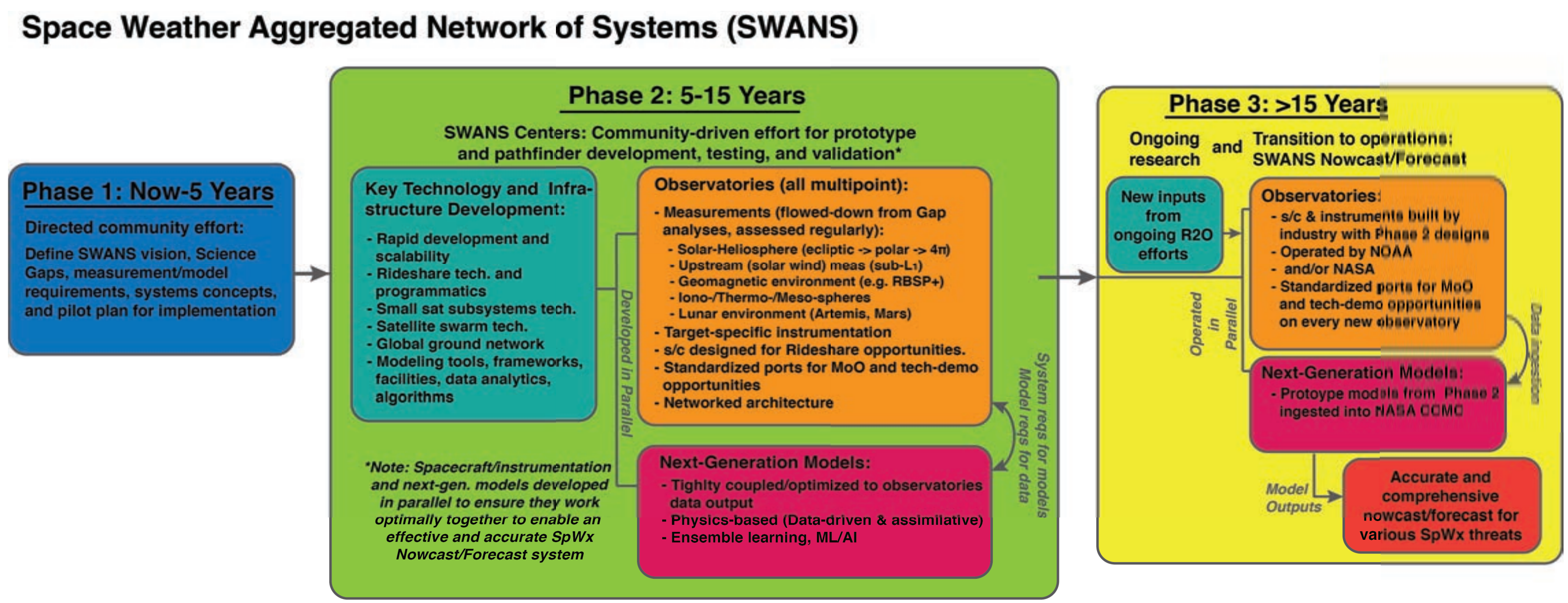

FIGURE E-10 Organization and implementation strategy of SWANS.
SOURCE: Vourlidas et al. (2023), https://doi.org/10.3847/25c2cfeb.d0925f85. CC BY 4.0.

E.5.2 Long-Term Goal 2: Establish an "Earth-Independent" Deep Space Weather Nowcasting and Forecasting Capability for Mars and Other Solar System Locations of Interest in Support of the Artemis Program and Potential Commercial Activities

By the end of the coming decade, NASA's Artemis missions will develop the necessary technologies and lay the foundations to send humans to Mars in the following decade. Human and robotic space exploration will continue to extend farther from Earth, and the space weather conditions in these target locations need to be studied and understood to facilitate flight safety. Owing to speed-of-light communications delays, space weather forecasting in these increasingly distant locations will need to rely on resources local to the mission transport vehicle and/or habitat to monitor conditions and generate warnings, without communication to/from mission control.

The panel notes that Mars is not a specifically critical location for heliophysics science, but owing to NASA's plans for the Artemis missions, there is a necessary obligation for the space weather community to take Mars into consideration and provide space weather monitoring and forecasting in support of astronaut health and Artemis technological systems. This will require new vantage points of the Sun as well as new in situ measurements covering Mars and its approaches.

Long-Term Goal 2 Strategy: There are many unique challenges presented by a mission to Mars, and space weather efforts will need to extend beyond cislunar space in support of these future missions. The panel makes the following suggestions:

Characterize and Monitor Space Weather Up to a Few AU, at Mars and on the Martian Surface

The panel suggests developing capabilities that can monitor the space weather environment at Mars and provide measurements for the development and validation of models. These capabilities include

- Continuous full-Sun observations, building on the capabilities developed through the priority goals, in order to ensure that CMEs can be continuously tracked in both Sun–Earth and Sun–Mars directions and enable more accurate and reliable SEP event warnings to astronauts in transit to/from and on the surface of Mars.
- A space weather monitor at Earth–Sun L4 with potential instruments to include a magnetograph, coronagraph, heliospheric imager, X-ray monitor, radio spectrograph, EUV imager, energetic particle detectors (electrons, protons, heavy ions), and solar wind plasma and magnetic field instruments capable of supporting forecasts for Mars orbital transfer and Mars surface missions. An Earth–Sun L4 monitor is identified in the priority goals to enable eruption and SEP forecasting at Earth. In the following decade, such a monitor will moreover become a priority for exploration missions, as it provides space weather forecasting support for likely orbital transfer trajectories to and from Mars.
- A Mars–Sun L1 monitor that provides continuous, unobstructed coverage of solar UV irradiance, solar activity (magnetogram, coronagraph, EUV, and X-ray imagers), and interplanetary conditions (energetic particle detectors, solar wind and magnetic fields). This set of measurements would establish a space weather monitoring capability at Mars, a key step in preparing for the arrival of humans at Mars.
- Spacecraft in orbit around Mars to provide additional key magnetospheric and atmospheric measurements and support communications infrastructure.

Also needed is funding for research studies and modeling efforts required to understand and forecast space weather drivers and impacts at Mars. These include improved global MHD solar wind, CME propagation and SEP models developed and validated for Mars. There is also substantial fundamental research needed to gain a comprehensive space weather understanding of a planet with a thin atmosphere and no global magnetosphere.

Enable Stand-Alone Forecasting Capability at Mars

- As astronauts in transit to Mars or on the Martian surface may experience significant communication delays with Earth, they will need space weather forecasts and alerts generated locally to the astronaut to allow for a fast response to changing conditions. The panel suggests that NASA develop the necessary space weather instruments to be located onboard orbiting spacecraft at Mars, transit vehicles, and on the Martian surface to provide data in real time.

- Fund and develop models capable of ingesting local observational inputs and with a capacity to run on the computer systems available to distant astronauts (e.g., tablets, laptops, desktop computers) to provide actionable forecasts in a timely manner.
- The panel suggests that NASA take full advantage of the upcoming Artemis lunar missions to design and prototype onboard space weather instrumentation packages and develop monitoring and forecasting tools for stand-alone use by astronauts.

Related Priority Goals and Strategies

A number of the identified short-term priority goals build toward the scientific understanding and forecast capabilities required to achieve long-term goal 2, including the following:

Goal 1: Develop a reliable 12-hour lead time probabilistic >M1 of solar eruption and potentially associated SEP events forecast with a 6-hour lead time; and *Goal 6: Develop a reliable probabilistic All Clear forecast with multiday lead time*. Pre-eruptive, longer lead time and All Clear flare and SEP forecasts are required for day-to-day mission planning and mitigation of adverse impacts—in particular, the protection of crew health by informing them when it is safe to carry out EVAs or allowing them time to construct or return to a radiation shelter and to safeguard avionics. Accurate probabilistic forecasts specifically are required for decision-making and managing risk. Space weather monitoring from the Earth–Sun L4 location is doubly beneficial in that it also informs the space weather conditions for the Hohmann transfer orbit, a likely orbital path choice for humans to travel to Mars. Simultaneous full-Sun observations of the Sun enable space weather monitoring and forecasting for Mars throughout its entire orbit.

Goal 3: Characterize and monitor the space weather environment in cislunar space and on the lunar surface in support of the Artemis program. Many lessons learned for improved modeling of the cislunar environment can be carried forward to the Martian environment—for example, observations returned from new energetic particle detectors monitoring the cislunar environment, the development of small instrumentation operating locally to the transit vehicle and/or an astronaut habitat to independently monitor human and hardware health without communication with Mission Control, and the development of models that more accurately characterize the energetic particle flux throughout the heliosphere. The deployment of an Earth–Sun L4 and/or full-Sun space weather package in the current decade will allow for the development of data products available from that location and forecasting models specific to Mars exploration.

Goal 9: Develop an accurate (to within ±20 percent) 6-month to 1-year forecast of the solar activity cycle. Predicting the gross characteristics (maximum, peak time, duration) of the solar activity cycle is relevant to mission planning involving long-duration human spaceflight, including missions to Mars. While radiation shelters provide astronauts with shielding from transient, relatively short-lived, low-energy SEPs, it is much harder to do so for higher-energy GCR particles. GCRs are modulated by the heliospheric magnetic field and thus are anti-correlated with sunspot number over the course of the solar cycle. Better forecasts of the solar activity cycle, in addition to shorter-term 6-month to 1-year predictions, will be advantageous for mission planners.

E.6 EMERGING OPPORTUNITIES

Assessment of emerging opportunities in this report are based on opportunities or "obligations" to support the safety of activities that are already starting or are foreseen to start over the coming years, and that are sensitive to space weather impacts. The consideration by the panel has not been limited just to space activities; it also includes ground-based and airborne activities where space weather can be considered as one of the main hazards. Some of the foreseen activities and application areas are mainly commercial, and this is foreseen to create other types of emerging opportunities for space weather service provision.

The space-based "emerging opportunities" considered here may also provide opportunities to enhance space weather monitoring by either utilizing information that is produced by the applications naturally, or, for example, by utilizing new space-based platforms as hosts for space weather monitoring instruments. This aspect is addressed in the discussion that follows.

E.6.1 Opportunity 1: Protection of New Space Activities

Over the coming years, human spaceflight activities are foreseen to increase substantially. A key driver for improved space weather information will be establishment of the Lunar Gateway and eventual return to the Moon. Commercial suborbital tourist flights have already been executed by Blue Origin and Virgin Galactic. When commercial space tourism evolves to full LEO flights and potential cislunar/lunar flights, it too will require information on radiation hazards from solar energetic particles (SEPs).

Human Activity in Cislunar/Lunar (Conducted and Served by NASA Aided by NOAA)

Humankind is returning to the Moon during the next few years, potentially with a long-term objective to establish a permanent presence there. The radiation environment during the flight to the Moon and on the Moon's surface is hazardous to humans and to the electronics of the spacecraft and any vehicles or equipment that is deployed. The panel views plans for a return to the Moon as an opportunity to highlight the importance of space weather information and as an obligation to support safety during transit and while working on the Moon's surface, for example, by providing sufficient warning time to seek shelter from radiation.

The radiation hazard during relatively short flights to the Moon is mainly associated with solar eruptions and potential SEP events associated with these eruptions. SEPs may potentially also impact communication and navigation systems that are critical for cislunar and lunar flights and human activities on the Moon's surface. The main needs associated with this emerging opportunity/obligation considered by the panel include

- Improved forecasting of SEP events, and nowcasting of the evolution and duration of the event and continuous provision of information during the event.
- Characterization of cislunar and lunar space weather environment.
- Forecasting and nowcasting of ionospheric disturbances impacting satellite communication.
- All Clear forecast for conditions with low risk of space weather activity.
- Characterizing surface charging of objects in the deep magnetotail, including at the Moon.

The needs associated with this opportunity/obligation are identified as priority goals by this panel.

- *Goal 1:* Develop an accurate and reliable 12-hour lead time probabilistic >M1 solar eruption forecast and associated SEP event forecast with 6-hour lead time.
- *Goal 3:* Characterize and monitor the space weather environment in cislunar space and on the lunar surface in support of the Artemis program.
- *Goal 6:* Develop a reliable probabilistic All Clear forecast with multiday lead time.
- *Goal 11:* Develop 30-minute to 1-hour lead time forecasts of transionospheric and skywave mode HF radio wave signal impacts (e.g., ionospheric scintillation, absorption) in polar, midlatitude, and equatorial regions.

An additional threat that is not yet well characterized is the potential for Earth magnetotail reconnection events to accelerate energetic electrons toward the Moon when it is within the magnetotail region (approximately 2–3 days/month). These electrons would penetrate directly to the Moon's surface—the Moon lacks both a shielding magnetic field and an atmosphere—and potentially cause vehicle and/or equipment electrical charging. A subsequent discharge could prove dangerous to astronauts or lunar tourists (see the next section) in the vicinity. The panel sees a need to better understand magnetotail reconnection events and their ability to generate surface charging fluxes out to the Moon's orbit. Thus, a related goal on understanding surface charging in inner geospace is the following:

- *Goal 8:* Develop a reliable probabilistic forecast of surface charging (3-day lead time), internal charging (28-day lead time), SEE (6-hour lead time), and event total dose (1-day least time) for all orbits.

The strategies for achieving these goals are described earlier in this report.

Space Tourism in LEO, Cislunar (Conducted by Private Sector, Served by NOAA/Private Sector)

The first fully commercial space tourist flights have already started: in 2021 by Blue Origin, and in 2022 by Virgin Galactic. While these suborbital flights are short and barely crossed the 100 km altitude Kármán line that is often used to define where outer space begins, there are plans to expand the tourism to full LEO orbital flights, including orbital hotels, and for commercial cislunar activities and flights orbiting around the Moon. Current suborbital flights require very limited space weather information, although it is not clear whether a launch would be executed during an SEP event. As soon as space tourism includes complete LEO orbital flights or longer-term stays on space hotels, information about the radiation environment in LEO and space weather impact on space operation will be required. If and when space tourism includes flights to cislunar or lunar environments, the need for radiation environment forecast and monitoring information increases dramatically.

The user needs for commercial space tourism for LEO, cislunar, and lunar operations are very similar to the needs of human exploration as described earlier in this report (e.g., in Section E.3.3, Goal 3) and they are supported by the same priority goals.

Because of the commercial customers for these services, however, this opportunity is potentially more geared toward commercial space weather service provision. The panel suggests that space agencies and public entities support development of operational, commercial third-party space weather services. Recent history has shown that commercial space weather services developed on government funding often falter when the government discontinues development support, suggesting that a transition period of government-funded operations and maintenance may be necessary to foster a thriving commercial services sector. Data buys from commercial actors and government agencies acting as anchor customers may be considered in supporting a transition period. It is also important to note that, at least at the beginning, the commercial service providers are unlikely to be able to implement and maintain the space segment facilitating the required forecasting and nowcasting services. Therefore, for this scenario, a publicly funded data acquisition system would need to be maintained and developed further.

E.6.2 Opportunity 2: Proliferated LEO

Orbital regions for operational missions are becoming increasingly congested. Over the past decade, the number of active satellites in space has increased by a factor of 7 from just over 1,000 to more than 7,000. At the same time, the quantity of debris is increasing, particularly in the LEO orbits increasingly used by operational space missions. At the end of 2022, the number of tracked objects in space exceeded 30,000. If efficient methods are not utilized, the probability of catastrophic collisions in orbit is predicted to increase significantly over the coming decades. This could lead to "Kessler syndrome," the situation in which the density of objects in orbit is high enough that collisions between objects and debris create a cascade effect, each crash generating debris that then increases the likelihood of further collisions. At this point, certain LEOs would become entirely inhospitable.

Space Weather Service to Space Traffic Coordination/Management and Space Sustainability

Space weather is both a positive and a negative factor in the domain of Space Traffic Coordination (STC)/ Space Traffic Management (STM) and sustainable use of outer space. Expansion of Earth's upper atmosphere owing to solar activity affects the atmospheric drag at orbits below 600 km and causes small debris to reenter and burn in the atmosphere. At the same time, space weather is the largest source of uncertainty in determining orbital trajectories of LEO satellites and debris objects. During severe geomagnetic storms in particular, satellites and debris are impacted by the increase in thermospheric density in LEO altitudes and, in worst-case scenarios, the orbital tracking catalog used in conjunction assessment and collision avoidance maneuver planning could be completely invalidated for several days. In addition, SEP events are a hazard to the safe launch and operation of satellites and can contribute to creation of new debris when satellites malfunction or their control is completely lost. Space weather is also one of the main contributors to the uncertainty of the impact site in the case of uncontrolled reentry of satellites and large debris such as rocket bodies.

Accurate thermospheric neutral density forecasts are needed for orbit prediction and satellite collision avoidance in LEO, and for prediction of satellite reentry time and location in the case of an uncontrolled reentry. Uncertainty in reentry location creates disturbances in other services—for example, in aviation owing to no-fly zones and a potential risk of impact on populated areas.

This opportunity is addressed by Priority Goal 2: Develop data-assimilative, thermospheric neutral-density models, including an integrated modeling framework for predicting LEO satellite and debris trajectories, capable of accurate and reliable forecasts during geomagnetic storms.

Other user needs and service requirements for STC/STM are not yet well defined. The panel suggests that these user needs need to be analyzed in close cooperation with the relevant regulatory entities and end users, including a gap analysis versus current space weather capabilities. The results from the gap analysis are foreseen to identify O2R/A2R opportunities for development of needed space weather capabilities.

Services to Commercial Operators

To ensure safe space operations and to support space sustainability, the panel anticipates that commercial satellite operators will be subject to the same STC/STM recommendations as public operators and space agencies. Commercial operators will also be expected to have financial interests in the safe operation of their satellites—for example, to avoid increased premiums in insurances of space assets. Future operations for in-orbit servicing and active debris removal will be particularly sensitive to any external disturbance because of the need for close proximity operations.

The panel considers space weather services to commercial operators as an emerging opportunity for commercial actors for business-to-business service provision. It is, however, unlikely that commercial operators will be able to implement their own space weather data acquisition infrastructure, particularly its space segment. Thus, data acquisition by public actors and making the data available for commercial use will be required. Space agencies need to ensure in particular the availability of baseline data from the Sun–Earth line, including in situ measurements from L1 and potentially from locations between L1 and the Sun. Improved SEP event forecasting, nowcasting, and monitoring would require a mission to the vicinity of L4 to monitor active regions that are beyond the west limb of the Sun as seen from Earth, but that are still magnetically connected to Earth.

The opportunity of space weather services to commercial operators is addressed by Priority Goal 2. However, in this case, the suggested strategy for developing commercial space weather services need to also be considered.

E.6.3 Opportunity 3: Protection of Emerging Applications Sensitive to Space Weather

Applications based on autonomous operation of space and ground vehicles are foreseen to emerge during the coming years. Space weather is a potential hazard increasing risks of such operations, creating an opportunity/obligation to provide information reducing the risk.

Autonomous Space Transport, Rendezvous, and Docking

Satellite close proximity operations required by future In-Orbit Servicing (IOS) and Active Debris Removal (ADR) services in LEO will, in most cases, be based on autonomous operation of the servicing spacecraft because the operation has to be executed outside the communication range of the operating ground station. Close proximity operations are extremely sensitive to external disturbances, and a software or hardware anomaly on either spacecraft may cause a collision and loss of one or both missions.

The space weather information needed by autonomous transport applications on the ground or in the atmosphere covers all aspects of space weather impacting satellite health, navigation, HF and satellite communication, and the radiation and plasma environment. Priority Goals 1–5, 7, 10, and 11 identified by this panel, and the strategies to reach those goals, serve these needs well.

Many autonomous space transport applications and particularly IOS and ADR will be operated by commercial entities; this is another domain where an opportunity for commercial space weather services can be expected to open. Thus, the suggested strategy for developing commercial space weather services needs to be considered also in this domain.

Autonomous Ground, Maritime, and Aerial Transport

Vehicles controlled remotely by human operators are already in operational use in many application areas including transport, remote sensing, mining, and military applications. Over the coming years, some of these vehicles are foreseen to become autonomous and able to operate without continuous interaction with a human operator. Autonomous delivery drones and robots are already being used for food deliveries, and drones able to deliver small packets are planned by many delivery companies. The deployment of autonomous maritime transport ships is also on the horizon (MARPRO 2023) and autonomous UAVs for military applications are under development.

All autonomous vehicles are sensitive to potential space weather impacts through disturbances in satellite navigation, HF/satellite and GNSS communication issues, and impacts by energetic particles during SEP events on onboard software or hardware. These disturbances create a potential hazard of loss of control, leading to collisions with other vehicles, ground-based infrastructure, or people. Military operators also need information to distinguish natural disturbances from intentional human action. Space weather services that support mitigating these risks and support safe operation of such vehicles is considered another emerging opportunity/obligation.

The space weather services needed to support autonomous transport applications cover all types of events impacting navigation, communications, and radiation environment within the atmosphere. Timely alerts and warnings are crucial to enable operators to take mitigating actions. These needs are addressed by the Priority Goals 11 and 12. The need for forecasting potentially hazardous conditions impacting vehicle operation is addressed by Priority Goals 1, 4, and 8.

Autonomous transport applications, except military ones, will be executed by commercial companies, and the panel considers this another emerging opportunity for commercial space weather services. Thus, the suggested strategy for developing commercial space weather services is applicable here.

Distinguish Natural Impacts from Human Action in a Contested Space Environment

While this topic has always been an important part of space weather information, the panel highlights it here because of the increasingly contested and congested environment in space. When there is a satellite anomaly or loss of contact to a space asset, it is extremely important for the responsible operators to be able to quickly assess the probability of a natural impact causing the anomaly. In military applications, such information needs to be considered mandatory.

The needs of this opportunity/obligation are addressed by all priority goals suggested by the panel.

E.6.4 Opportunity 4: Enhancement of Space Weather Monitoring

Space missions associated with the emerging opportunities in this report also offer a potential opportunity to enhance space weather and space environment monitoring capability. Many commercial missions carry instruments that produce useful data, including platform magnetometers for satellite attitude determination, dosimeters or radiation monitors, and other instruments observing the environment around the satellite. The panel suggests that NASA and NOAA investigate the possibility of making this data available to the research community through targeted data buys or partnerships with commercial satellite operators. An illustrative example is the recent evaluation of GNSS Precise Orbit Determination (POD) data from the Starlink constellation for use in thermospheric density model data-assimilation schemes.

The panel suggests that data-buy activities could be expanded significantly with other LEO satellite constellation operators. For example, NASA, through its Commercial Smallsat Data Acquisition program, has purchased radio occultation (RO) data from several companies, including GeoOptics and Spire Global Subsidiary. NOAA has also made RO data buys, recently issuing contracts with Space Sciences and Engineering PlanetiQ (Golden, Colorado) and Spire Global Subsidiary. RO data are used for research in the atmospheric sciences and climate and for numerical weather prediction, but these data would also be very useful for ionospheric research and monitoring.

Commercial missions also offer potential opportunities for hosted payload instruments, and the panel suggests that utilization of these flight opportunities be carefully considered. The GOLD instrument onboard SES-14 telecommunication satellite is an example of utilizing such a hosted payload flight opportunity. More systematic utilization of such flight opportunities would benefit from studies on the capabilities of commercial constellation providers, instrument miniaturization, utilization of dense observation networks, and standardized interface modules and scientific sensors for potential mass manufacturing. The panel suggests that NASA maintain the pipeline instrument concept to procure selected science-grade instruments and to be ready to utilize flight opportunities that may materialize on short notice. Further details of such an approach are included in the Applications of Commercial Constellations for Expanded Science and Space Weather (ACCESS) program proposed for the next-generation LWS architecture (Rowland 2023).

The new capabilities implemented for the Artemis missions may also offer opportunities to enhance space weather monitoring in cislunar and lunar environments. These opportunities include, for example, CLPS missions, Lunar Gateway, ride-along opportunities with the launches to the Moon, the planned communication and navigation satellite constellations around the Moon, and the Artemis Base Camp on the Moon surface. The panel suggests that NASA consider how benefits from the ACCESS approach, including standardized interface modules (see, e.g., St. Cyr et al. 2000) and sensors, instrument miniaturization and data buy from commercial operators, could be utilized in the Artemis framework.

E.6.5 Opportunity 5: Innovation Pathways

Recent progress by the space weather enterprise is poised to leverage new assets and new computational capacity to serve the rapidly expanding needs in space utilization. In this emerging sector, development plans for capacity enhancement in space weather hazard assessment and geospace observability have been actively aligned and influenced by planned and upcoming satellite missions and ground-based observational programs.

Utilization of data from science missions in operational space weather applications is not new—for example, for more than 2 decades the Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory satellite (SOHO) has been used as the main instrument for operational CME onset detection. The Advanced Composition Explorer (ACE) was launched in 1997 and continues to provide real-time solar wind data as it orbits the L1 libration point some 1.5 million km upstream from Earth. Many planned upcoming NASA science missions, including Polarimeter to Unify the Corona and Heliosphere (PUNCH), Geospace Dynamics Constellation (GDC), and the Interstellar Mapping and Acceleration Probe, are anticipated to have near-real-time downlinks to allow the use of the data in space weather operation with the support of NOAA.

The panel suggests that such quick data downlinks be considered for more science missions to facilitate the utilization of the measurement data both for scientific research and for space weather operations.

E.6.6 Opportunity 6: International Space Weather Coordination

Countries and governments around the world are increasingly aware of the risk caused by space weather and solar activity on the critical infrastructure on Earth. The approaching solar maximum is contributing to this awareness as, for example, frequent display of aurora at lower latitudes is showing undeniable evidence of the Sun–Earth interaction. In Europe, many nations have included space weather into their national risk register, typically at the same level as other major natural risks like earthquakes, volcanic eruptions, and flooding (e.g., "UK National Risk Register 2023 Edition"; HM Government 2023).

As a result of the increased awareness, space weather has become part of many international forums. The UN Committee on Peaceful Uses of Outer Space (COPUOS) established the first international Expert Group C

(Space Weather) as part of the Long-Term Sustainability of Out Space Activities (LTS) in 2011. The follow-on Space Weather Expert Group reporting to UN COPUOS under a permanent agenda item was approved in 2015. One of the results of the work by this group was a letter in July 2022 from the UN Office for Outer Space Affairs (UNOOSA) to the World Meteorological Office (WMO), Committee on Space Research (COSPAR), and International Space Environment Service (ISES) to lead efforts to improve the global coordination of space weather activities in consultation and collaboration with other relevant actors and international organizations, including the UN COPUOS. The first international meeting on this context was held in November 2023 in Geneva.

The Coordination Group for Meteorological Satellites (CGMS) has been coordinating space weather observations by operational satellite missions since the establishment of the CGMS Space Weather Coordination Group (SWCG) in 2018. The SWCG supports the continuity and integration of space-based observing capabilities for operational space weather products and services throughout CGMS and the user community and the CGMS operators with regard to space weather phenomena. Particularly, the SWCG coordinates space weather activities within and across CGMS working groups, including space weather data, ensuring that space weather operational measurements are incorporated into the CGMS baseline, relevant frequencies, anomaly resolution, products, knowledge, and policy.

At present, there is no similar coordinating forum for scientific space-based space weather observations. In addition, there is no international coordinating forum for ground-based operational or scientific space weather observations. The panel suggests that such a coordination group would be established to facilitate joint international efforts to ensure the continuation and enhancement of space weather observations for scientific research. One potential approach for such a group could be the International Agency Space Weather Coordination Group (IASWCG) model presented in the November 2023 meeting organized by WMO, COSPAR, and ISES in Geneva.[21]

Space weather is also a topic in many international conferences. The most well-known conferences focusing mainly on space weather include the annual Space Weather Workshop in the United States, European Space Weather Week (ESWW), the Asia-Oceania Space Weather Alliance (AOSWA), the Space Weather Observations Throughout Latinoamerica (SWOL) workshop, and the Conference on Space Weather organized in the framework of the American Meteorological Society (AMS) annual meeting. Space weather and heliophysics-related sessions are also regular parts of the European Geophysical Society (EGS) and American Geophysical Union (AGU) meetings.

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[21] "The idea of this International Agency Space Weather Coordination Group would be that it would be a forum for those agencies that fund space weather research and observations to plan, coordinate and partner to implement space weather activities. In some ways, it is a reboot of ILWS [International Living with a Star]." James F. Spann Jr., Senior Scientist, Office of Space Weather Observations, NOAA/NESDIS, "International Agency Space Weather Research and Mission Coordination Forum," presented at the 45th Scientific Assembly of the Committee on Space Research (COSPAR), July 13–21, 2024, Busan, South Korea, https://www.cospar-assembly.org/uploads/documents/Finalprogram-2024.pdf.

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ANNEX E.A

ORGANIZATIONAL DEVELOPMENT OF THE SPACE WEATHER ENTERPRISE

In recent years, key aspects needed to grow the space weather framework have been put in place through a national interagency push to organize and coordinate all aspects of space weather, including research, nowcasting, forecasting, protection, mitigation, readiness, response, and recovery. In 2014, the Office of Science and Technology Policy (OSTP) in coordination with the National Science and Technology Council (NSTC) formed the interagency task force on Space Weather Operations Research and Mitigation (SWORM). Through SWORM, more than 30 governmental departments and agencies were brought together to develop the National Space Weather Strategy (NSWS) and the National Space Weather Action Plan (NSWAP). Released in 2015, NSWS and NSWAP established a connection between the national and homeland security and the science and technology enterprises.

The strategy and action plan set goals to establish benchmarks for space weather events; enhance response and recovery capabilities; improve protection and mitigation efforts; improve assessment, modeling, and prediction of impacts of critical infrastructure; improve space weather services through advancing understanding and forecasting; and increase international cooperation. Further efforts toward national coordination resulted in Executive Order 13744, "Coordinating Efforts to Prepare the Nation for Space Weather Events," in October 2016 and the Space Policy Directive, "Reinvigorating America's Human Space Exploration Program," in December 2017. In 2019, the National Space Weather Strategy and Action Plan (NSWSAP) was updated, focusing on three objectives: (1) enhancing the protection of national security, homeland security, and commercial assets and operations; (2) developing and disseminating accurate and timely space weather characterization and forecasts; and (3) establishing procedures for responding to and recovering from space weather events.

The updated NSWSAP emphasizes the critical importance of maintaining baseline observation capabilities. It highlights that future advancements in space weather monitoring and prediction will depend on the development of new technologies and innovative methodologies. Additionally, it stresses the need for enhanced coordination and collaboration not only across various federal agencies but also with the commercial sector, academic institutions, and international partners. The Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act was signed into law in December 2020. The act defined space weather roles for NOAA, NASA, NSF, and DoD, specified key space weather priorities, established the Space Weather Advisory Group (SWAG), and established a National Academies of Sciences, Engineering, and Medicine Government-University-Commercial Roundtable on Space Weather. NOAA has reorganized all of its future space weather satellite observations (L1, GEO, and LEO) under a single NESDIS office—Space Weather Observations (SWO)—located at NASA's Goddard Space Flight Center (GSFC). SWO manages NESDIS's space weather programs from inception to launch (NESDIS 2024). NOAA is currently developing the Space Weather Follow-On at L1 (SWFOL1) operational mission, which focuses on priorities from the PROSWIFT Act to track coronal mass ejections (CMEs) with remote coronal imaging and to sustain space monitoring of in situ solar wind and interplanetary magnetic field (IMF) measurement upstream of Earth at L1. NOAA's GOES-U satellite, the last of four in the GOES-R series of geostationary operational environmental satellites, launched on June 25, 2024. Now called GOES-19, the spacecraft includes an operational coronagraph. NOAA has also begun implementation of the next generation of these high-priority measurements and is also partnering with ESA's Vigil mission for off-Sun–Earth line capability. Lastly, NOAA has begun preformulation of the next generation of space weather observations from geostationary orbit.[22]

Additional developments since the past decadal are discussed below.

E.A.1 User Engagement Surveys

The 2015 Action Plan called for a "comprehensive survey of space-weather data and product requirements needed by user communities to help improve services." Conducted by Abt Associates, the *Customer Needs and*

[22] This paragraph was updated after the release of the report to reflect NOAA's current space weather program.

Requirements Survey for Space Weather Products and Services report was published in 2019 (Abt Associates 2019). This report highlighted the specific needs of users in the electric power, satellite, and aviation sectors and emergency managers, as well as the diverse user base reliant on Global Navigation Satellite Systems (GNSS). Additional user surveys are being performed by the SWAG compliant with directives in the PROSWIFT Act. In September 2024, the SWAG published, "Results of the First National Survey of User Needs for Space Weather."[23]

E.A.2 Space Weather Benchmarking

The SWORM interagency task force released the *Space Weather Phase 1 Benchmarks* report in 2018. Following the report release, NSF and NASA requested that the Institute for Defense Analyses (IDA) make recommendations to improve the Phase 1 benchmarks, including identifying any outstanding gaps. This led to the release in 2019 of the "IDA Next Step Space Weather Benchmarks" document, written by a 32-member panel of experts chaired by Geoffrey Reeves (NSTC 2018).

The authors of the IDA document were divided into five working groups: geo-electric fields, ionizing radiation, ionospheric disturbances, solar radio bursts, and upper atmosphere expansion. The recommendations from these groups are detailed in the IDA report and include the following:

- Completing the national-scale magnetotelluric (MT) survey;
- Addressing gaps in the ionizing radiation species and energy ranges for which data are available;
- Taking new space-based observations with instruments at Earth–Sun L1 to measure solar energetic particles (SEPs) and with instruments in Earth orbit to measure SEPs and galactic cosmic rays (GCRs);
- Creating new benchmark quantities to better characterize ionospheric disturbances;
- Collecting solar radio data with continuous coverage of the Sun, with the necessary frequency coverage, frequency range, polarization, and dynamic range to determine high-fidelity benchmarks;
- Ensuring that future solar EUV observational missions have sufficient overlap to enable cross-calibration and have the spectral resolution needed for thermospheric modeling and forecasts; and
- For all subdisciplines, creating benchmarks, including statistical uncertainties, that characterize space weather events that occur more frequently than the more extreme 1-in-100-year events.

E.A.3 Quad-Agency Memorandum of Understanding (NASA, NSF, NOAA, Department of the Air Force)

In 2018, NASA, NOAA, and NSF signed a "Tri-Agency MOU," facilitating the coordination of research topics in support of the National Space Weather Strategy. In December 2023, the Department of the Air Force joined in what is now referred to as a "Quad-Agency Memorandum of Agreement (MoA)." The MoA enables the agencies to coordinate and support efforts to facilitate the transition of space weather data and modeling capabilities to U.S. space weather prediction providers. It also facilitates feedback from prediction providers to the research community to improve research and operational forecasts.

E.A.4 Formation of the Space Weather Advisory Group

Composed of representatives from academia, the commercial space weather sector, and nongovernmental end users, the SWAG was established by the PROSWIFT Act to be an advisory body to the SWORM interagency working group. In 2023, SWAG delivered a report, "Findings and Recommendations to Successfully Implement PROSWIFT and Transform the National Space Weather Enterprise," as an input to an upcoming update to the 2019 NSWSAP (SWAG 2023). In particular, the 2023 SWAG report,

[23] "Results of the First National Survey of User Needs for Space Weather Product of the Space Weather Advisory Group," 2024, https://www.weather.gov/media/nws/Results-of-the-First-National-Survey-of-User-Needs-for-Space-Weather-2024.pdf.

> Identifies the urgent need to adequately fund the space weather enterprise to address persisting risk from space weather and better meet the growing and changing needs of invested parties. To this end, SWAG identified 25 findings with 56 recommendations which, if implemented, will provide the funding, processes, support, and structure to foster transformative change across the national space weather enterprise.

In an ongoing effort, the SWAG is carrying out an updated user requirements survey.

E.A.5 Formation of the National Academies Space Weather Roundtable

The National Academies' Space Weather Roundtable was established in 2022 by the PROSWIFT Act. The roundtable brings together senior managers, decision makers, and scientists from government, the commercial space weather industry, and universities to discuss activities to facilitate advances in the scientific understanding of space weather phenomena, the impacts of space weather, and the forecast of space weather events. The roundtable facilitates communication and knowledge transfer among government participants in the SWORM Interagency Working Group, the academic community, and the commercial space weather sector.

E.A.6 NASA Space Weather Science and Applications Program

The Heliophysics Division's Space Weather Science Application (SWxSA) program expands the role of NASA in space weather science under a single budget element and supports the multiagency NSWSAP. SWxSA competes ideas and products, leverages existing agency capabilities, collaborates with other national and international agencies such as NSF, and partners with user communities to facilitate the effective transition of science knowledge to operational environments. In 2023, this program was renamed the Space Weather Program (SWxP).

Under this program, NASA established—in collaboration with CCMC, SRAG, and NOAA SWPC—the Moon to Mars Space Weather Analysis Office in 2020 to support NASA's human exploration activities. The office provides space weather assessments and anomaly analysis to support NASA robotic missions across the heliosphere.

E.A.7 NASA Small Business Innovation Research Program

One way NASA has engaged the commercial sector for space weather research has been through the Small Business Innovation Research (SBIR) Program for Space Weather. According to NASA (2020), four space weather technology proposals were selected for Phase I in the SBIR program in 2019, and six more in 2020. Two more proposals were selected for Phase II in 2018. NASA describes these efforts as ranging from developing model techniques, tools to support space weather extremes, and measurement technologies to measure radiation levels aboard aircraft.

E.A.8 Additional Space Weather Roles and Priorities Defined

The White House 2022 document "Space Weather Research-to-Operations and Operations-to-Research Framework" describes the ways in which the agencies are engaged in R2O-O2R; the roles for each agency; and the testing, development, and validation framework for new products and models to become operational (White House 2022).

E.A.9 Federal Emergency Management Agency

In 2019, FEMA released *National Threat and Hazard Identification and Risk Assessment (THIRA): Overview and Methodology* (FEMA 2019b). In this document, FEMA assessed the effects of the most catastrophic threats and hazards to the nation; space weather and pandemic were identified as one of just two natural hazards with the potential to have impacts nationwide. Also in 2019, FEMA released *Federal Operating Concept for Impending Space Weather Events* (FEMA 2019a) to inform federal departments and agencies on actions to take for an impending space weather event. This document focused on the operational and crisis planning functions, reporting structure, and reporting requirements of departments and agencies in response to notification of a forecasted space weather event.

ANNEX E.B

SPACE WEATHER VALUE OF PROPOSED MISSIONS

As discussed in the main part of this report, the three discipline-oriented science study panels—Panel on the Physics of the Sun and Heliosphere (SHP); Panel on the Physics of Magnetospheres (MAG); and Panel on the Physics of Ionospheres, Thermospheres, and Mesospheres (ITM)—examined numerous concepts for future solar and space missions, many based on community input papers submitted in response to an invitation to the research community. The study panels mapped concepts against their prioritization of science targets in their respective disciplines and provided the survey steering committee with a short list for consideration. This list was narrowed down to 12 concepts that subsequently underwent further analysis. As part of this analysis, members of the space weather science and applications panel were asked to examine each concept and report back to the steering committee on its relevance ("value") to the panel's particular areas of concern in the space weather domain. The panel was also asked to consider if the value of a concept could be increased substantially via relatively small and affordable augmentations to the baseline concept. Table E.B-1 summarizes the results of the panel's work; it is followed by a summary of the analysis that informed the panel's judgments for each concept.

A word about nomenclature: In this annex, the panel refers to missions named Firefly, HELIX, and Lynx. These were the names in use when the panel completed its analysis. Subsequently, these missions were renamed by the steering committee to better represent what they would accomplish. The results were that HELIX became Heliospheric Dynamic Transient Constellation (HDTC); Firefly became Ecliptic Heliospheric Constellation (ECH); and Lynx became Links (not an acronym; short for Links Between Regions and Scales in Geospace). The missions themselves did not change.

E.B.1 Space Weather Contributions from the BRAVO Mission Concept

Mission Concept Summary

The Buoyancy Restoring-Force Atmospheric-Wave Vertical-Propagation Observatory (BRAVO) is a five-spacecraft mission with all spacecraft in 500–600 km circular orbits (Table E.B-2). Three spacecraft (M1, M2, and M3) share an orbital plane in a string-of-pearls configuration with separations of ~4 minutes and ~20 minutes respectively (along track). The remaining two spacecraft (S1 and S2) are in equivalent circular orbits with orbital planes on either side of the M1, M2, and M3 track such that they are separated by ~2,500 km (cross-track from the lead spacecraft M1) at midlatitudes. The inclination of the orbit is not set, but 45–55 degrees is referenced in the TRACE documents. The instrumentation on each spacecraft is tuned to support the 3D specification of thermospheric properties within the satellite configuration.

BRAVO also contains a mission-critical ground-based component, consisting of a meteor radar network (estimated at ~50 stations) and global TEC maps. The meteor network will produce global-scale neutral wind measurements providing context (background wind field) to interpret LiDAR and NIRAC measurements, helping to couple mesoscale and continental-scale (1,000 km) wind structures and allow for 3D reconstructions of gravity waves in that volume.

Space Weather Value of the Mission as Proposed (Table E.B.-3)

Value to Space Weather Research

The primary value to space weather research of the BRAVO mission is associated with its detailed measurements of ionosphere–thermosphere coupling. Understanding the multiscale vertical coupling of lower ITM boundaries will improve system-level modeling of energy and mass transport in the ITM system.

- **PR1:** ***(High)*** **Neutral density measurements** from BRAVO's ground-based and spacecraft mission segments will combine to sample spatial scales of the neutral winds not previously studied. This will

TABLE E.B-1 Space Weather Augmentation Suggestions Summary for Proposed Concepts

Mission	Real-Time Downlink	Precision GNSS	GNSS RO	Visible Imager	FUV Imager	EUV Imager Additional Bandpasses	X-ray Imager	Electron Plasma (keV)	Charge/ Discharge Sensor	Energetic Electrons (MeV)	Energetic Protons (MeV)	Energetic Ions (MeV-GeV)	Misc
BRAVO	High							Low	Low		High		
ICE-CIRCUIT	High						Low			Medium			
COMPASS													Medium: turn on particle sensors in crusie phase. Low: add dosimeters
COMPLETE	High										High	High	High: In situ solar wind + IMF, white light coronagraph. Low: move "L4" s/c to 90 deg
FireFly	High					Medium	Low					Low	
Helix	High					Low						Low	Medium: Incline orbit of 1 s/c
ISP													Low: dosimeters
Lynx	High								High				High: comm relay
OHMIC	High	Medium					Low	Medium	High	Medium	High		
RESOLVE	High		Medium					Medium	High	Medium	High		(These blow the mass budget, except GNSS RO and maybe RT DL)
Solaris	High						Low				High	High	Low: Extra s/c
Source	High	Medium					Low	Medium	High	Medium	High		

NOTE: Acronyms are defined in Appendix H.

TABLE E.B-2 BRAVO Nominal Mission Configuration

Central Orbital Plane (M1, M2, M3)	Bracketing Orbital Planes (2), S1 and S2
M1 • Nadir-oriented Na LiDAR • Near-IR airglow imager (NIRAC) • GNSS RO M2 and M3 (identical) • Near-IR airglow imager (NIRAC) • GNSS RO • Terahertz Limb Sounder (TLS)	S1 and S2 (identical) • GNSS RO • Terahertz Limb Sounder (TLS) • FUV 135.6 nm Imager

NOTE: Acronyms are defined in Appendix H.

TABLE E.B-3 Summary of BRAVO's Potential Value to Space Weather Research and Operations

IDs	Mission Value for SWx	Mission Aspect of Interest	Impact on Research or Operations?	Priority
Mission as Proposed				
PR1 and PO1	Characterization of thermospheric neutral density	Low-latency, multipoint measurements of thermospheric neutral density.	Research and Operations	High
PR2	Characterization of thermospheric neutral winds and temperatures	Spatial scale sufficient to advance understanding of thermospheric gradients and coupling in ITM system.	Research	High
PO2/PR4	Improved modeling of coupled upper atmosphere–ionosphere	RO profiles and TEC profiles.	Operations	Medium
PR3	Characterization of energy transfer between lower atmosphere and ionosphere–thermosphere	Imaging of gravity wave field.	Research	Medium
Mission Augmentations				
AR1, AR2, AR3	Radiation and charging environments at LEO and energetic particle precipitation impacting the ionosphere–thermosphere system	If able considering strict mass restrictions on the mission as proposed: Add energetic particle (tens keV to MeV electrons, SEP ions) and charge/discharge sensors to each observatory.	Research	Low (charging/electrons) to High (protons)
AR4	Spacecraft altitude drag and neutral density measurements	Expansion of GNSS capacity to include POD in addition to RO.	Research and Operations	Medium
AO1	Real-time space weather data stream	Add real-time downlink of SWx-relevant data.	Operations	High

NOTES: IDs are identification codes used and assigned below; PR: as proposed value to space weather research; PO: as proposed value to space weather operations; AR/AO: same with mission augmentations. Acronyms are defined in Appendix H.

directly enable key science in multiscale thermospheric coupling. Measurements of this caliber would also support coupled model development for the lower ITM, enabling studies/quantification of timescales for atmospheric driver impacts on, for example, satellite drag.

- **PR2:** ***(High)*** **Neutral wind and temperature measurements** are key to models of the coupled ionosphere–atmosphere system. BRAVO will specifically measure quantities sufficient to address conditions under which lower atmospheric processes can drive the thermospheric state (forcing from below). Na LiDAR measurements will provide vertical wave structure in neutral temperature, while the ground-based meteor radar network and TLS will provide bulk and local flow structures (meridional and zonal winds). Furthermore, the LiDAR and TLS can provide mean-state vertical resolution of neutral temperature, all keys to modeling the coupling of spatial and temporal scales (and coupling) in the neutral wind structure and energy.
- **PR3:** ***(Medium)*** **Horizontal gravity wave field** measurements from BRAVO will be provided by the three spacecraft in the central orbital plane. Sequential images from the three NIR cameras can be stitched together to map out the gravity wave field. These measurements are important for quantifying the spatiotemporal dependence of the lower atmosphere gravity wave momentum/energy flux incident on the ionosphere–thermosphere (in coordination with PR2).
- **PR4:** ***(Medium)*** **Ionospheric electron density structuring** via TEC maps (2D at assumed hFoF2, or 3D tomographic) are heavily utilized in various areas of global space weather research. BRAVO targets multiscale TEC measurements via ground-based global TEC maps, together with spacecraft GNSS RO measurements to give more local line-of-sight coverage (geometry dependent). The structuring of the electron density in the range 90–400 km (up to spacecraft altitude) can readily be utilized to model ionospheric structuring associated with thermospheric dynamics, or equally utilized in magnetosphere–ionosphere coupling to study forcing (from above) of ionospheric state. These measurements will be similar to existing GNSS RO (Spire, COSMIC, ePOP, etc.) and will enhance the number of available measurements (however, not dramatically with 5 spacecraft).

Value to Space Weather Operations

The primary value to space weather operations of the BRAVO mission is associated with thermospheric density and GNSS RO measurements, both of which couple to current nowcast products. The number of spacecraft and their configuration will not provide global information, but nonetheless could be readily available with ~90-minute latency to support relevant drag products or supplement global TEC relevant products.

- **PO1:** ***(High)*** **Neutral-density measurements** are operationally important for resident space object tracking—specifically, the propagation and prediction of orbital elements for collision assessments. Current operational models, such as NRLMSISE, are semi-empirical, relying on relatively simple algorithms, and are climatological in nature. BRAVO will provide Limb Sounders along three closely spaced orbital planes. With ~95-minute latency (assuming one download per orbit) the data would likely be useful for augmenting current model information as well as when combined with appropriate data assimilation model development. If integrated into an operational platform, this would be a significant step forward, adding support for data-driven augmentation to satellite drag calculations, a capacity that is not currently available.
- **PO2:** ***(Medium)*** **GNSS RO measurements** are theoretically readily integrated with other RO measurements (e.g., Spire, COSMIC-2) to provide data assimilation inputs to tropospheric/stratospheric and upper atmospheric/ionospheric numerical weather prediction models. BRAVO RO would enhance available data (number of RO profiles/day) for assimilative, operational models of the fully coupled atmospheric system. RO measurements can be inverted to provide TEC profiles in the ionosphere, which could contribute to operational assessments of ionospheric conditions for RF communications, over-the-horizon radars, and GNSS reception. With low-latency data retrieval, it is possible to provide key data that will enhance ionospheric nowcasting information for space weather operations.

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

Value to Space Weather Research

Several possibilities exist for augmentations to BRAVO that would extend past data sets. These additional sensors could enable us to learn how to process and exploit their data in real time, and they could be used in scientific studies and AI/ML models benefiting from the more extensive context data provided by the modern heliophysics observation system.

- **AR1:** ***(High)*** **Add ~1–100 MeV proton sensors to one vehicle.**
  - Low-altitude proton gradients and their solar cycle variation are one of the largest uncertainties in satellite design (climatology) models.
  - Not needed on all vehicles because apparently not high enough inclination to provide rapid monitoring of geomagnetic cutoffs to reveal their local time structure.
  - Prior analog: SAMPEX PET (low altitude <600 km), RBSP/ECT (high altitude).
- **AR2:** ***(Low)*** **Add charge/discharge sensors to all observatories.**
  - BRAVO orbits transit the inner zone and slot, where charging is believed to occur and has not been directly observed. Considering this, spacecraft charging data—such as charge/discharge sensors, and/or spacecraft potential monitoring—would prove valuable for space weather research. There is no flight history of surface charging/discharge sensors in LEO.
  - Low ranking because the outer zone and aurora are where charging is more likely and are not accessible if inclination is below 55 degrees.
  - Prior analog: SCATHA, CRRES.
- **AR3:** ***(Low)*** **Add 40 keV to 5 MeV electron sensors to all observatories.**
  - Nominal energy range 40 keV to 5 MeV.
  - Low-altitude electrons in this energy range are also a major source of error in climatology models used for satellite design.
  - Priority is low owing to low inclination—misses most of outer belt and aurora/plasma sheet.
  - Prior analog: RBSP ECT/RBSPICE, THEMIS SST+ESA.
- **AR4:** ***(Medium)*** **Add Precise Orbit Determination (POD) capacity to RO observatories.**
  - POD provides an indirect approach for evaluating atmospheric mass density via determination of drag. This would provide additional density measurements at the altitude of the spacecraft (~500 km).
  - Prior analog: Swarm, Sentinel-6.

Value to Space Weather Operations

- **AO1:** ***(High)*** **Addition of real-time downlink for space weather relevant data beacons.**
  - Real-time thermospheric observations would likely prove very valuable to data assimilative models of the thermosphere and its effect on satellite drag.

E.B.2 Space Weather Contributions from the Interhemispheric-Circuit Mission Concept

Mission Concept Summary

Interhemispheric-Circuit (I-Circuit) is a 12-spacecraft mission with two distinct flight elements. The high-altitude mission element contains two identical spacecraft (Hi-1 and Hi-2) in out-of-phase Molniya-like orbits (apogee ~12 Re), with apogee over the south/north pole respectively. The high-altitude element carries multiband FUV imagers, providing global-scale images in four passbands (OI 135.6 nm, N2 LBHs 140–150 nm, N2 LBHl 165–180 nm, and H 121.8 nm) with 1-minute resolution and ~50 km ground sampling distance. It further contains in situ electron measurements of the 10 eV to 1 MeV via an electron spectrometer (10 eV to 30 keV) and an energetic electron detector (30 keV to 1 MeV).

The low-altitude element contains 10 spacecraft in 600 km altitude circular, polar orbits. These satellites are distributed across four intersecting orbital planes. (Two of the spacecraft must be closely spaced, <4 km, in the auroral zone to facilitate the curlometer approach.) The satellites are phased to allow for the collection of in situ data from both hemispheres simultaneously. The LEO mission element characterizes the ionosphere–thermosphere via the magnetic field (at spacecraft via a magnetometer, and at ~80 km via the MEM instrument), plasma drift, electric field, atmospheric constituent densities (H, O, O_2, N_2, NO, and O^+), oxygen temperatures, and local pitch angle–resolved energy spectra of precipitating electrons (10 eV to 30 keV).

Summary of instruments:

- HEO (2 spacecraft), each with
  - Multiband FUV Imager
  - Electron Spectrometer (10 eV to 30 keV)
  - Energetic Electron Detector (30 keV to 1 MeV)
- LEO (10 spacecraft), each with
  - Magnetic Field Instrument
  - Ion Velocity Meter
  - MEM Instrument (DC electric field)
  - Electric Field Probe (AC electric field)
  - FUV Spectrograph
  - THz Limb Sounder
  - Electron Spectrometer (10 eV to 30 keV)

Space Weather Value of the Mission as Proposed (Table E.B-4)

Value to Space Weather Research

The primary value to space weather research of the I-Circuit mission is associated with simultaneous sampling of precipitation (magnetospheric inputs) and ionosphere and thermosphere dynamics.

- **PR1:** ***(High)*** **Global auroral imaging** from a Molniya-like orbit would provide global maps of electron energy flux and characteristic energy, as well as provide key measurements of auroral boundaries. These measurements have been lacking since the days of Polar (2005) and Image (2008) and are sorely missed in the scientific community.
- **PR2:** ***(High)*** **Neutral density measurements** aboard 10 LEO platforms will enhance information about spatial and temporal scales of thermospheric density variations and enable key science in ionosphere–thermosphere coupling. The range of spatial scales accomplished via the four intersecting orbital planes have not been directly observed and are extremely important for multiscale coupling and drivers within the ITM system. Measurements of this caliber would also offer validation and assimilation data for coupled magnetospheric and ITM-system models, enabling, among other things, studies of driver impacts (atmospheric and magnetospheric) on LEO satellite drag.
- **PR3:** ***(Medium)*** **Neutral wind and temperature measurements** are key to models of the coupled ionosphere–atmosphere system. For example, these parameters are necessary to understanding the conditions under which lower-atmospheric processes can drive the thermospheric state (forcing from below) and under what conditions magnetospheric/ionospheric processes can drive thermospheric state (forcing from above), and the multiscale coupling between the two. I-Circuit measurements of the winds and temperature via the THz imagers will directly enable advancement of these topics by supplying data at a combined temporal and spatial resolution not sampled before. Furthermore, the direct measurements via the deployable "dropper" probes would give unique (direct) measurements of neutral winds. This will have value for space weather research via enhancing the physics of whole atmosphere models.
- **PR4:** ***(Medium)*** **In situ plasma.** Hot electron plasma (~10 keV) causes surface charging, and its altitude structure is not well known. Charging hazard may be particularly intense through the high-latitude auroral zone. Improved surface-charging plasma climatology models contribute to more efficient, robust spacecraft designs. Having the same measurements on the LEO and HEO spacecraft can potentially provide

TABLE E.B-4 Summary of I-Circuit's Potential Value to Space Weather Research and Operations

IDs	Mission Value for Space Weather	Mission Aspect of Interest	Impact on Research or Operations?	Priority
Mission as Proposed				
PR1	Dual-hemisphere auroral activity, full oval coverage	Full hemisphere specification of auroral boundaries and energy input.	Research (if augmented Operations)	High
PR2, PO1	Characterization of thermospheric neutral density	Low-latency, multipoint measurements of thermospheric neutral density.	Research and Operations	High
PR3	Characterization of thermospheric neutral winds and temperatures	Spatial scale (and altitude profiles) sufficient to advance understanding of ITM coupling.	Research	Medium
PR4	Satellite charging environment	Observations required to improve models of satellite charging environments throughout geospace.	Research	Medium
PR5	Characterization of ionospheric current density	Altitude-resolved, mesoscale current densities.	Research	Medium
Mission Augmentations				
AR1	Spacecraft charging environment	Global characterization of high-energy auroral input (>keV electrons that cause surface charging, X-ray imager).	Research (if augmented, Operations)	Low
AR2, AR3	Spacecraft charging environment and energetic particle precipitation inputs to atmosphere/ionosphere systems	Add energetic particle instruments to all low-altitude spacecraft and differential energy measurements on high-altitude spacecraft.	Research	Medium
AO1	RT Auroral Global Activity (full oval)	FUV real-time images.	Operations	High

NOTES: IDs are identification codes used and assigned below; PR: as proposed value to space weather research; PO: as proposed value to space weather operations; AR/AO: same with mission augmentations. Acronyms are defined in Appendix H.

opportunities during HEO ascent and descent for coordinated studies of precipitation mechanisms and acceleration. Furthermore, the 600 km altitude, 10 spacecraft LEO mission segment will provide insight into the spatial scales of hot electron precipitation.

- **PR5: (*Medium*) Current density** in the region of current closure would provide extremely valuable data for coupling models of the IT system. These data would be new, as they sample scale sizes from a few tens of km to a few hundreds of km, a scale size not currently available for systematic studies of current structures. I-Circuit measurements would also be the first systematic, true measurements of the altitude variations of currents, providing key insights into mesoscale coupling of currents to the global system.

Value to Space Weather Operations

No real-time downlink is planned for the proposed mission in its *current* format. The high-altitude element would therefore be limited to a ~12-hour minimum latency (one orbital period), the LEO element on the order of 90 minutes, or less depending on number of downlink stations (based on con-ops plan of four orbital planes and spacecraft separation along orbital track).

- **PO1: *(High)* Neutral-density measurements** are operationally important for resident space object tracking—specifically, the propagation and prediction of orbital elements for collision assessments. Current operational models, such as NRLMSISE, are semi-empirical, relying on relatively simple algorithms, and are climatological in nature. I-Circuit will provide 10 Limb Sounders along four orbital planes. With ~95-minute latency (assuming one download per orbit) the data could be useful for augmenting current models when combined with appropriate model development. If integrated into an operational platform, this would be a tangible step forward, adding a data-driven augmentation to satellite drag calculations, a capacity that is not currently available.

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

Value to Space Weather Research

- **AR1:** ***(Low)*** **Add X-ray imager to high-altitude spacecraft.**
    - X-rays are slightly more relevant for surface charging than UV.
    - Higher altitude complicates achieving valuable resolution.
    - Prior analog: Polar PIXIE (Polar Ionospheric X-ray Imaging Experiment).
    - Also consider including a visible imager (or higher-luminosity bands). This could enable higher-resolution and more detailed auroral images and data content. (See community input papers by M. Henderson [2022] on the need for better global auroral images and J. Rodriguez [2022] on continuous auroral imaging in FUV.)
- **AR2:** ***(Medium)*** **Add energetic particle telescopes to all low-altitude spacecraft.**
    - Hundreds keV to many MeV electrons and ions deposit considerable energy flux into the atmosphere and ionosphere systems; these ought not be neglected and are also relevant for spacecraft charging details in the proliferated LEO environment and the determination of particle cutoffs, which are used as an input to aviation radiation models.
    - Particle precipitation is also critical to the mission science.
- **AR3:** ***(Medium)*** **Add energetic particle telescopes on high-altitude spacecraft to provide energy-resolved, differential intensities from more than one look direction.**
    - Single-direction, integral fluxes are insufficient for their science and also relevant radiation environment (e.g., see HEO energetic particle observations: Fennell et al. 1997).

Value to Space Weather Operations

- **AO1:** ***(High)*** **Addition of real-time downlink to two high-altitude spacecraft for space weather relevant data.**
    - Near-real-time global auroral imagery of the northern hemisphere would improve/replace existing space weather operational systems (i.e., Ovation Prime). It would further allow development/demonstration of real-time auroral products (e.g., electron surface charging, scintillation probability maps, etc.).

E.B.3 Space Weather Contributions from the Comprehensive Observations of Magnetospheric Particle Acceleration, Sources, and Sinks (COMPASS) Mission

Mission Concept Summary

Comprehensive Observations of Magnetospheric Particle Acceleration, Sources, and Sinks (COMPASS) is a Large Strategic Science class mission. The goal of the mission is to explore the “heart” of Jupiter’s radiation belt region, a previously unexplored area, to understand how what may be the solar system’s greatest particle accelerator works. COMPASS consists of a single spacecraft launched on Falcon Heavy and uses an Earth gravity assist to reach Jupiter in approximately 6 years.

The COMPASS science payload consists of the following instruments:

- Thermal Plasma Detector (TPD): electrons and ions with composition from 10 eV/Q to 6 keV/Q.
- Suprathermal Particle Detector (SPD): ~3 keV/Q to 300 keV/Q ions with composition and charge state.
- Energetic Particle Detector (EPD): 25 keV to 1.5 MeV for electrons, 50 keV to >10 MeV for protons, and 150 keV to >10 MeV for O and S.
- Relativistic Particle Detector (RPD): 1.6 MeV to >19 MeV for electrons, 17 MeV to >100 MeV for protons.

- Ultra-Relativistic Particle Detector (UPD): 10 MeV to >50 MeV for electrons, >1 GeV for protons, >100 MeV/nuc for O and S.
- Fluxgate Magnetometer (FGM): DC magnetic fields from a few Hz to ~10 Hz.
- Search Coil Magnetometer (SCM): AC magnetic fields from 10 Hz to 20 kHz.
- Electric Field Waves (EFWs): AC electric fields from 50 Hz to 400 kHz.
- X-Ray Imager (XRI): X-ray photons from 0.5 to 5 keV.
- Education and Public Outreach Camera (EPOC): Not a science instrument (same as JunoCam from NASA's Juno mission).

The proposed concept of operations for COMPASS is that during Earth gravity assist, radiation instruments will be cross-calibrated with other HSO components as well as checkouts during the cruise phase. Once the observatory reaches Jupiter's orbit, it will complete several deep dives into the core radiation belt and synchrotron regions, including close flybys of the Jovian moons Io and Callisto. The mission lasts 514 days, completing 15 orbits, and ends with impact into Jupiter. The nine science instruments provide full energy range coverage of the charged particles, full spectrum wave measurements, the first X-ray imager in the Jovian environment, and a public outreach camera.

Space Weather Value of the Mission as Proposed (Table E.B-5)

Value to Space Weather Research

The main value to space weather research is understanding the extreme exposure of Jupiter's harsh radiation environment.

- **PR1:** ***(Medium)*** **Radiation belt conditions and effects.** Jupiter's radiation belts represent one of the most hazardous radiation environments in the solar system. Experience learned here on designing instruments to survive and monitoring their performance in this environment will help future spacecraft design and deployments throughout the solar system.

TABLE E.B-5 Summary of COMPASS Potential Value to Space Weather Research and Operations

Mission as Proposed				
IDs	Mission Value for Space Weather	Mission Aspect of Interest	Impact on Research or Operations?	Priority
PR1	Radiation belt physics	Understanding of radiation belt particle acceleration and loss mechanisms under extreme conditions.	Research	Medium
PA1	Satellite performance in radiation environments	Long-term operations in the heart of the Jovian radiation belts will provide spacecraft performance in the most challenging radiation environment in the solar system.	Applications	Medium
Mission Augmentations				
IDs	Mission Value for Space Weather	Suggested Augmentation	Impact on Research or Operations?	Priority
AR1	Adverse effects of radiation during deep-space operations and Jupiter orbit	Add dosimeters to measure exposure enroute to Jupiter and throughout operations in Jupiter orbit.	Applications	Low
AR2	GCR and SEP intensities between 1 and 5 AU	Run the EPD/RPD/UPD sensors (plus magnetometer and plasma for context) routinely during the cruise phase to Jupiter.	Research and Applications	Medium

NOTES: IDs are identification codes used and assigned below; PR: as proposed value to space weather or space climate research; PO: as proposed value to space weather operations; AR/AO: same with mission augmentations. Acronyms are defined in Appendix H.

Value to Space Weather Operations or Applications

The mission as proposed will make no observations of value to space weather operations, but measurements of an extreme radiation environment and satellite performance therein are of value to space weather applications such as spacecraft shielding and mission design.

- **PA1:** ***(Medium)*** **Satellite performance in radiation environments.** Long-term operations in the heart of the Jovian radiation belts will provide rare data on SPACECRAFT performance in extreme radiation environments. Previous NASA missions have already explored the Jovian environment, so this is not a high-value element of the mission.

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

The mission could potentially increase its benefit to space weather mitigation research and future deep space vehicle design by augmenting its payload with a compact dosimeter instrument that would record total ionizing dose information throughout during the Jupiter transit.

- **AR1:** ***(Low)*** **Long-term effects in deep space.** Strategically located dosimeters to study the exposure during deep-space transit to Jupiter and within the extreme Jovian radiation environment. Addition of variable shielding around the dosimeters could also validate new High-Z shielding designs in an extreme environment.
- **AR2:** ***(Medium)*** **GCR and SEP observations during cruise.** COMPASS energetic particle, plasma, and magnetometer instruments could be run continuously or more routinely (compared to "annual checkouts" described in the proposed mission concept) during the cruise phase to Jupiter, enabling valuable measurements of the GCR environment between 1 and 5 AU and potentially also SEP propagation and intensities in deep space beyond 1 AU.

E.B.4 Space Weather Contributions from the COMPLETE Mission Concept

Mission Concept Summary

COMPLETE is a flagship mission concept combining broadband spectroscopic imaging and comprehensive magnetography from multiple viewpoints around the Sun to enable tomographic reconstruction of 3D coronal magnetic fields and associated dynamic plasma properties, which provide diagnostics of energy release. The mission architecture and design achieve all objectives with three total observatories: one orbiting Lagrange point L4 and two positioned at L1 (designated L1 and L1'). COMPLETE has a 7-year design life with a 5-year prime mission during which all the observatories are located in their "fixed" positions. The mission will require two Falcon Heavy launches in 2032 and 2033, 6 months apart.

COMPLETE implements two targeted instrument suites—a broadband spectroscopic imager and a comprehensive 3D vector magnetograph. All instrument designs are derived from previously formulated or flown instruments, with appropriate engineering modifications required for COMPLETE.

The EUV and X-ray imaging spectrometers at L1 will be pointed heliocentric westward, extending from 0 to 3 $R_\odot$ West. The imaging spectrometers on the L4 spacecraft will be pointed at disk center, extending from ±1.5 $R_\odot$. The two photospheric vector magnetographs on L1 and L4 will provide an optimal observing area that extends from –60° to 120° heliographic longitude.

Instruments summary:

- [L1] EUV filtergram imager in 131 and 193 Angstrom passbands
- [L1] SXR spectroscopic imager from 1–50 Angstroms
- [L1] HXR spectroscopic imager from 10–100 keV
- [L1'] Full γ-ray spectroscopic imager from 0.02–8 MeV

- [L1] ENA spectroscopic imager from 0.02–5 MeV
- [L1, L4] Photospheric vector magnetograph
- [L1] Lyman-alpha Hanle coronagraph from 1.1–3 $R_\odot$ (descope option)

Space Weather Value of the Mission as Proposed (Table E.B-6)

Value to Space Weather Research

Like the Firefly and HELIX missions, the COMPLETE mission concept employs multiple spacecraft to obtain simultaneous multipoint measurements of the Sun. Its focus on understanding the mechanisms by which energy

TABLE E.B-6 Summary of COMPLETE's Potential Value to Space Weather Research and Operations

IDs	Mission Value for SWx	Mission Aspect of Interest	Impact on Research or Operations?	Priority
Mission as Proposed				
PR1	Improved understanding of energy release in solar eruptions/flares and identification of signatures of energy release.	EUV imager, broadband spectroscopic imager, photospheric vector magnetograph.	Research	High
PR2, PO1	Photospheric magnetic field observations of magnetically well-connected active regions to Earth and for missions to Mars.	EUV imager, photospheric vector magnetographs at L1 and L4.	Research and Operations	High
PR3	3D reconstruction of the coronal magnetic field for modeling of active region configurations and input into solar wind models.	EUV imager, photospheric vector magnetograph, Lyman-alpha Hanle magnetograph.	Research	High
PR4	Gamma-ray observations may provide information about flare acceleration of SEPs, but this is an unproven research avenue at present.	γ-ray spectroscopic imager.	Research	Low
Mission Augmentations				
AO1	Near-real-time downlink for spacecraft at L4 to provide images of active regions that are magnetically well connected to Earth.	Continuous X-band NRT beacon data downlink of EUV and magnetograph imagery.	Operations	High
AR1, AO2	Improved understanding of SEP production and transport in inner heliosphere.	The addition of energetic particle instruments would improve understanding and predictability of SEP intensity and extent throughout the heliosphere.	Research and Operations	High
AR2	Understanding and improved modeling of inner heliospheric solar wind structure.	In situ measurements of solar wind characteristics (density, speed, temperature, mag field) on both spacecraft.	Research	High
AO3	Detection and measurement of CMEs from multiple vantage points.	Wide-angle white-light coronagraph on both L1 and L4 spacecraft.	Operations	High
AO4	Better coverage of the far side for active emergence and eruption monitoring	Place "L4" spacecraft at 90 degrees from Sun–Earth Line.	Operations	Low

NOTES: IDs are identification codes used and assigned below; PR: as proposed value to SWx research; PO: as proposed value to SWx operations; AR/AO: same with mission augmentations. Acronyms are defined in Appendix H.

is stored in the solar corona and impulsively released in the form of eruptions is well suited to supporting space weather research goals.

This evaluation is made on the version of the mission developed for the TRACE in which there are photospheric vector magnetographs on both the L1 and the L4 spacecraft, but only one coronal magnetic field measurement from the L1 spacecraft. The fact that this coronal magnetic field measurement is not on both spacecraft and is an apparent descope target makes the mission less compelling for space weather research because its primary discovery value lies in determining the 3D structure of pre-eruptive coronal magnetic field configurations. Descoping the coronal magnetic field measurement would eliminate its most important discovery potential and make this mission less appealing to space weather research.

The lack of any helioseismic investigation component of the mission also makes it less compelling for space weather research focused on better understanding and prediction of the solar activity cycle. While surface magnetic fields are the most visible manifestation of the solar cycle, measurement of subsurface flows from two vantage points in the ecliptic could provide valuable insights into the nature of the cyclic dynamo.

- **PR1: *(High)* EUV imager, broadband spectroscopic imager, photospheric vector magnetograph.** The range of instruments on COMPLETE that are dedicated to measuring magnetic energy storage and release in the solar corona ensures that it has the potential to significantly advance our understanding of solar eruptions, the root cause phenomenon behind all extreme space weather events.
- **PR2: *(High)* EUV imager, photospheric vector magnetographs at L1 and L4.** Off Sun–Earth line measurements of photospheric magnetic fields is of high value to space weather research because it enables tracking the evolution of active regions from the East limb to well beyond the West limb. Simultaneous EUV imaging, including from beyond the West limb, will enable identification of eruption events that are magnetically connected to Earth or to spacecraft in the Earth–Mars transit orbit.
- **PR3: *(High)* EUV imaging and photospheric vector magnetic field measurements from L1 and L4 combined with coronal magnetic field measurements from L4.** While a Ly-alpha spectropolarimeter has not been demonstrated for use in measurement of coronal magnetic field, and it is doubtful that a single instrument/viewpoint can reconstruct 3D coronal magnetic fields, a successful demonstration of this capability would likely open new avenues for observation and analysis of solar eruptions.
- **PR4: *(Low)* γ-ray spectroscopic imager.** Gamma-ray observations of solar eruptions were accomplished by the Compton and RHESSI observatories and are currently made by the Fermi Large Angle Telescope. These data have not proven useful to understanding or predicting solar activity, and this capability is thus rated as low value to space weather research.

Value to Space Weather Operations

The fact that COMPLETE would fly spacecraft only to the L1 and L4 Lagrangian points means that it will not be capable of full Sun observations. In particular, these two Lagrangian point spacecraft can measure magnetic field over only about 210 degrees in solar longitude, and they will not observe the polar latitudes. This lack of more complete solar observations makes the mission less compelling to space weather operations. Also, the lack of any coronagraphic imaging capabilities makes COMPLETE less useful in detecting and modeling large solar eruptions on, or just beyond, the West limb, which can be the most SEP-productive eruptions (at Earth or in cislunar space). Similarly, the lack of any solar wind or energetic particle detectors makes the mission significantly less valuable to space weather operations than the other multiview solar missions.

- **PO1: *(High)* EUV imager, photospheric vector magnetographs at L1 and L4.** The combination of two instruments with major relevance to space weather forecasting and nowcasting (EUV imager and photospheric magnetograph) at two locations with off Sun–Earth line observations from L4 makes the COMPLETE mission of high value to space weather operations. As noted, even higher value would have been achieved with coronagraph and in situ SEP instrumentation on board.

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

Value to Space Weather Research

The lack of any in situ instrumentation on the baseline COMPLETE mission severely hampers its ability to analyze SEP events and/or solar wind and CME structures that might intersect both spacecraft. For example, CMEs at 1 AU are often much wider than the 60-degree separation between L1 and L4, so in situ measurements of solar wind characteristics at both locations would be of high value to research into structural evolution of plasma clouds as they propagate to 1 AU. The same holds for SEP events. This multiple-viewpoint simultaneous measurement capability may also be key in developing accurate and reliable CME and SEP forecasting models.

- **AR1:** ***(High)*** **Energetic particle detectors (1 to >400 MeV protons, up to 1 GeV/n ions) on both spacecraft.** The addition of energetic particle instruments would increase the value of this mission, as this could improve our understanding of SEP extent/connectivity with measurements at both L1 and L4. Furthermore, GCR is an important input to all space radiation analysis (SEEs on satellites, radiation shielding studies, astronaut health).
    - A pair of SEP instruments, such as SIS + HET from Solar Orbiter, to measure H-Fe from 1 to >400 MeV/nuc, can be implemented to satisfy the requirements that GOES-R uses for its SGPS and EHIS instruments (protons and heavy ions up to Ni from 1–>500 MeV/nucleon). Further increasing heavy-ion measurements to 1 GeV/nuc would allow characterization of the GCR.
- **AR2:** ***(High)*** **In situ measurements of solar wind characteristics (density, speed, temperature, magnetic field) on both spacecraft.** These observations are needed to understand the solar wind structure, density fluctuations, composition, and magnetic field, and to determine how the solar wind varies with longitude throughout the solar cycle.

Value to Space Weather Operations

Several relatively straightforward augmentations to the COMPLETE mission would increase its value to space weather operational forecasting and nowcasting.

- **AO1:** ***(High)*** **Continuous X-band NRT beacon data downlink of EUV and magnetograph imagery.** The lack of a near-real-time beacon downlink severely restricts the value of the mission to operational space weather forecasting and nowcasting. Addition of such a link would enable valuable off-Sun–Earth line magnetic field and EUV imaging to be incorporated into eruption and SEP warnings and alerts.
- **AO2:** ***(High)*** **Energetic particle detectors (1 to >400 MeV protons, up to 1 GeV/n ions) on both spacecraft.** The ability to measure SEP flux at both spacecraft separated by 60 degrees with identical instruments would greatly aid in warning and alerting deep-space operators in cislunar and Earth–Mars transit orbits of potentially dangerous incoming SEP events.
- **AO3:** ***(High)*** **Wide-angle white-light coronagraph on both L1 and L4 spacecraft.** The ability to image CMEs from L1 and L4 simultaneously would greatly enhance our ability to model CMEs and hence improve on the accuracy of arrival time and arrival speed estimates. The panel considered suggesting the inclusion of Heliospheric Imager instruments on both spacecraft, but felt that this would have made the augmentation list excessively long for a mission that is clearly trying to minimize instruments for cost savings.
- **AO4:** ***(Low)*** **Place "L4" spacecraft at up to 90 degrees from Sun–Earth line.** It is possible to station spacecraft anywhere in a 1 AU orbit around the Sun with the same fuel budget as required for station keeping at L4 or L5 and with only slightly more complex communications logistics. Given this, it may be preferable for the "L4" spacecraft of COMPLETE to be stationed at a larger angle from Earth, up to 90 degrees, that optimizes the solar surface coverage with other mission constraints and achieves a significantly larger solar far-side view while still maintaining overlap with the L1 magnetograph field of view.

E.B.5 Space Weather Contributions from the Firefly Mission Concept

Mission Concept Summary

Firefly is a four-spacecraft constellation mission in the Large Strategic Science class (>$2 billion full mission cost with reserves) with two spacecraft at high heliolatitudes (about 70 degrees aphelion of 2 AU and perihelion of 1 AU), and two near the ecliptic plane in quadrature with the Sun–Earth line. All four combined provide close to 4π-steradians of angular coverage of the solar sphere, enabling full exploration of the solar polar regions for the first time, simultaneously with observations from the ecliptic plane. Each spacecraft pair carries remote sensing (Doppler magnetograph, EUV coronal imager, white light [WL] coronagraph, and heliospheric imagers) and in situ (particles and fields package) payloads. The concept assumes two separate launches on Falcon Heavy–class launchers: one for the polar pair and one for the ecliptic pair.

The polar pair uses a Jupiter gravity assist to reach a highly inclined (~70 degrees relative to the ecliptic) orbit near 1 AU. Solar electric propulsion is used to circularize their orbits and increase their relative phasing by ~180 degrees within ~6 years of launch. The ecliptic pair is launched into near-circular orbits at 1 AU. Each spacecraft is parked between 90–120 degrees relative to the Sun–Earth line, with one placed ahead of Earth and the second placed behind. The primary mission design requirement is to acquire nearly complete coverage of the solar sphere for >80 percent of the prime mission. The cruise phase lasts ~5 years for the ecliptic pair acquiring data continuously and ~6 years for the polar SC, during which the instruments will collect science data but not continuously. The polar spacecraft will be in safehold during the high-radiation environment of the JGA, but the mission profile could accommodate planetary science rideshares for study of the Jovian magnetosphere.

Instruments:

- Doppler Vector Magnetograph in the Fe I/Ni I 5476Å passband
- Extreme Ultraviolet Imager with passbands in 171 and 304Å
- White-Light Coronagraph
- Solar Spectral Irradiance
- White-Light Heliospheric Imager
- Fluxgate Magnetometer
- Faraday Cup
- Solar Wind Composition (SPICES)
- Energetic Particle Suite (SIS+EPT-HET)

Space Weather Value of the Mission as Proposed (Table E.B-7)

Value to Space Weather Research

The primary value to space weather research of the Firefly mission lies in its nearly continuous full-Sun observing profile. This promises to drastically improve study, monitoring, and ultimately predictability of some of the fundamental drivers of heliospheric space weather such as solar eruptive events, coronal holes and high-speed solar wind streams, and co-rotating interaction regions. Firefly will remove known gaps and blind spots (farside and polar regions) on solar and solar wind observations relevant to the drivers of space weather. It will improve our understanding of the generation of the solar magnetic field, the origin of the solar cycle, and the causes of solar activity by providing regular polar magnetic field measurements and measurements of subsurface polar flows via helioseismology. A complete simultaneous view of the solar surface will help to understand and monitor the whole development of the active regions critical to understanding solar flares, large eruptions of fast coronal mass ejections (CMEs), and solar energetic particle events. Multiple viewpoints can also address vector magnetic field ambiguities and enable tomographic and/or stereoscopic methods, yielding information on magnetic energy, helicity, and field line topology. Daily downlink will be especially useful for polar magnetic field measurements.

- **PR1: *(High)* Polar and ecliptic magnetic field measurements.**
  - *Doppler Vector Magnetograph* provides photospheric magnetic field images and Doppler velocity images important to understanding the sources of solar variability, such as active regions, eruptive

TABLE E.B-7 Summary of Firefly's Potential Value to Space Weather Research and Operations

IDs	Mission Value for SWx	Mission Aspect of Interest	Impact on Research or Operations?	Priority
Mission as Proposed				
PR1, PO1	Characterization and predictability of active region development and eruptions on the solar disk.	Magnetograph and EUV imagers on the poles and the ecliptic plane simultaneously. Daily full-sun magnetic field measurements.	Research and Operations	High
PR2, PO2	Improvements on CME analysis, lead time, impacts, and also shock particle acceleration.	Coronagraphs and heliospheric imagers on the poles and the ecliptic plane in conjunction with in situ energetic particle measurements. Near-real-time component.	Research and Operations	High
PR3, PO3	Understanding of the energy absorption in the ITM system. Tracking active regions (ARs) over their entire lifetimes to develop better understanding of how irradiance varies with AR magnetic evolution.	Solar spectral irradiance observations from a "full Sun" perspective will improve understanding of UV and EUV outputs that drive ITM thermodynamics.	Research and Operations	Medium
PR4	Understanding and improved modeling of inner heliospheric solar wind structure.	In situ measurements of solar wind density and solar magnetic field measurements for better coronal magnetic field models of the entire solar sphere.	Research and Operations	High
PR5, PO5	Understanding the longitudinal extent of SEP events and their impacts on instruments and humans in space.	In situ energetic particle measurements in the ecliptic off the Sun–Earth line and out of the ecliptic. Polar spacecraft will be in Sun–Earth and Sun–Mars planes twice per year.	Research and Operations	High
PR6	Improved understanding of the solar cycle.	Helioseismic measurements of the polar region convection zone.	Research	Medium
Mission Augmentations				
AR1, AO1	Understanding and improved predictive modeling of active region development and flare site evolution.	X-ray irradiance measurements.	Research and Operations	Low
AO2	Radiation impacts.	Inner heliosphere GCR measurements from 500 MeV/nuc to 1 GeV/nuc.	Space climate research, Operations	Low
AR2	Understanding active region evolution to eruptive states; monitoring eruptive structures such as filaments (chromosphere/304) and sigmoids (coronal/131).	EUV passbands in one telescope need to be 195 (not 171) and 304. Suggested augmentation: second EUVI telescope observing hot coronal plasma (e.g., 131 and 94 Å passbands).	Research	Medium

NOTES: IDs are identification codes used and assigned below; PR: as proposed value to SWx research; PO: as proposed value to SWx operations; AR/AO: same with mission augmentations. Acronyms are defined in Appendix H.

events, coronal holes, and helioseismology studies. This provides observations needed to understand the interior of the Sun, such as rising magnetic fields of emerging active regions. These measurements are also immediately crucial to improve solar magnetic field and solar wind modeling, as the primary input to all solar wind models is the full-Sun photospheric magnetic field. Currently, models have to make rough assumptions on unobserved regions of the solar sphere, especially in the polar regions. Firefly provides measurements of both poles at the same time, and it will offer multipoint image evidence of the development of active regions and the evolution of solar eruptions. This is essential to improve

predictive solar eruption and energetic particle models that currently lack reliability for regions more than 45-degrees circle on the center disk in the Sun–Earth line.
 - *Extreme Ultraviolet Imager (heritage STEREO)* at both the poles and the ecliptic plane will help understand eruptions in all directions and improve CME source measurement and prediction of the arrivals of CMEs in deep space essential for deep-space exploration.
- **PR2: *(High)* Coronagraph and HI observations made over the poles simultaneously with the ecliptic plane.**
 - *White Light Coronagraph (heritage STEREO and SOHO)* will help measure the true extent of the shock and accurate CME propagation directions providing information about CME longitudinal deflection and the longitudinal extent of the CME-driven shock needed to determine full CME properties.
 - *White Light Heliospheric Imager (heritage SoloHI).*
- **PR3: *(Medium)* Solar irradiance measurements.**
 - *Solar Spectral Irradiance instrument (heritage SDO/EVE)* measures the variation in solar electromagnetic energy output. This overlapping with the EUV instrument will observe the Fe IX and XVI emission lines that are experienced in the coronal dimming during eruption of CMEs. This type of measurement is necessary to understand changes in Earth's upper atmosphere caused by the absorption of such energy and how it impacts the geospace environment, affecting satellite operations, communications, and navigation.
- **PR4: *(High)* In situ solar wind plasma and magnetic field.**
 - *Fluxgate Magnetometer (heritage multiple missions).*
 - *Faraday Cup (heritage Solar Probe Cup on PSP).*
 - *Solar Wind Composition (heritage ACE/SWICS, Ulysses/SWICS and Solar Orbiter/HIS).*
 - These observations are needed to understand the solar wind structure, density fluctuations, composition and magnetic field, and to determine how the solar wind varies with latitude and longitude throughout the solar cycle.
- **PR5: *(High)* In situ energetic particle measurements.**
 - *Energetic Particle Suite (heritage multiple missions)* is essential to understand energetic particle acceleration in and out of the ecliptic plane. While it is important for furthering understanding and forecasting capabilities, very little is known of the solar energetic particle environment out of the Sun–Earth line or ecliptic. Current models are limited in predictive capabilities owing to the sparse data acquired in the ecliptic plane and within 1 AU. Currently, there is a major focus on improving SEP models' predictive capabilities in support of human space exploration to ensure astronaut safety. This instrument suite measures the flux and composition of high-energy particles accelerated by flares, CME shocks, and CIRs, as well as cosmic ray flux. Furthermore, GCR is an important input to all space radiation analysis (SEEs on satellites, radiation shielding studies, astronaut health). GCR modulation is not fully understood at solar max, and GCRs are the highest risk for human exploration because it is difficult to shield from them relative to the SEPs.
 - The particle suite instrument will provide *electron and ion measurements* within the 10 keV–10 MeV and 10 keV/nuc–300 MeV/nuc, respectively.
- **PR6: *(Medium)* Improved understanding and predictability of the solar dynamo and solar cycle activity.** This will significantly advance our understanding of the solar dynamo and will improve the predictions of the solar cycle.

Value to Space Weather Operations

Firefly would provide continuous downlink beacon data for near-real-time space weather forecasting. The mission downlinks 6.4 GB of compressed data per day/per pair. The primary operational value of the low-latency data stream would be the daily full-Sun magnetic field measurements, including polar regions, that will significantly improve forecasting models of both background solar wind and CME propagation compared to current solar wind models, which use 27-day synoptic maps and extrapolated data for the polar and flux transport models for farside regions. CME observations from multiple viewpoints, including above the ecliptic, would add substantially to our knowledge of CME formation, acceleration, and evolution, as well as feeding improved CME data to propagation models to significantly improve arrival time predictions at Earth or other planets such as Mars.

Downlinking this volume of data daily requires 10-hour passes with NASA's Deep Space Network (DSN) 34 m ground stations for the ecliptic pair and polar pair. The science prime mission will last at least 4 years after final orbit insertion of the polar pair (10-year total mission duration).

Remote sensing: Having the multipoint magnetic field observations (from the poles and the ecliptic plane) will lead to the continuous assessment of the birth-to-death process of active regions needed to improve the modeling and predictive capabilities of solar eruptions that are the root cause of flares, CMEs, and solar energetic particle events. It will also improve synoptic measurements used as an input to operational solar wind models. Currently, solar magnetic field measurements are reliable only within 60 degrees of the disk center (as seen from Earth), thus greatly limiting our ability to drive predictive models of eruptions. Also, having coronagraph imaging from the poles at the same time from the ecliptic off the Sun–Earth line will improve the measurements for CME parameters, possibly decrease the lag time to get such parameters, and thereby improve CME arrival time estimates at Earth and other locations in the solar system such as Mars.

- **PO1:** ***(High/Medium)*** **Polar and ecliptic magnetic field measurements.** Having measurements on the active region development around the whole solar surface would increase the accuracy of models used for solar energetic particle forecasting and nowcasting. Note, with the Firefly mission CONOPS, these measurements are available only for ~2 months/year.
- **PO2:** ***(High/Medium)*** **Improved analysis of coronal mass ejections and shocks.** These near-real-time measurements are needed to understand the effects of the interaction of CMEs and solar wind HSS structures that significantly influence the arrival time at Earth and change the impact of such events with the geomagnetic storm characteristics. It will improve the current models used for CME arrival time forecasts (e.g., geomagnetic storm forecasting) and understanding and predicting SEP impacts at Earth (e.g., aviation industry), geospace (satellite industries), cislunar and Mars environments (e.g., astronaut health and single event upset, SEU, to vital exploration life-sustaining equipment) from CME driven shocks. It would serve as a proof of concept for the value of off Sun–Earth line observations made outside the ecliptic.
- **PO3:** ***(Medium)*** **Near-real-time solar irradiance measurements.** Ecliptic irradiance monitoring beyond L5 would give a longer 5- to 7-day advance forecast of EUV irradiance at Earth than that from L5 (3.5 days). Only a daily downlink of irradiance from the SPACECRAFT would probably suffice to update forecasts of thermospheric density, so NRT is not required.

In situ observations: The continuous in situ multipoint observations of solar energetic particles will improve current model predicting capabilities for warning time and peak intensity, and provide measurements needed to develop data assimilation models critical for future prediction capabilities for human deep-space exploration.

- **PO5:** ***(High)*** **In situ energetic particle measurements.** Add value of proton and heavy ion flux measurements and also electrons for SEP increase lead warning time. SEP composition is actually quite valuable information from a radiation perspective, because lighter elements and particles (ultimately electrons) can penetrate farther into materials/shielding/bodies at any given energy of interest, while heavier ions do more damage (more impactful on dose).

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

Value to Space Weather Research

- **AR1:** ***(Low)*** **Soft X-ray irradiance measurements.**
  - 0.1–0.8 nm and 0.05–0.4 nm passbands (i.e., see GOES observations) enable identification of solar flare events and classification using NOAA/SWPC's flare-class scale.

  - The X-ray instrument in the GOES/EXIS suite could be used for a cost estimate.
  - X-ray observations over the solar poles and off the Sun–Earth line would enable better understanding of active region and flare site evolution.
  - For additional cutting-edge research purposes, X-ray imaging and/or extension of passbands into the hard X-ray spectrum and finer sensitivity (than say RHESSI) would partially fill observational gaps in historic measurements that might enable advances in predictive capability.
- **AR2:** ***(Medium)*** **Additional/different EUV passbands.**
  - The Firefly HMCS specifies 171 and either 195 or 304Å as the two passbands in a single EUVI telescope.
  - 171 and 195Å images are both lower-temperature coronal plasma passbands and are therefore redundant. For one EUVI telescope, we suggest keeping the 195Å passband because it shows coronal holes more clearly than the 171Å passband and having 304Å as the second passband because it shows a chromosphere/transition region view of the atmosphere.
  - The panel suggests *adding a second EUVI telescope with 131 and 94Å passbands*. These passbands show hotter flare plasma and in combination with 195 and 304Å images from the first telescope could be used to classify the equivalent GOES X-ray magnitude of flares via established regression models.

Value to Space Weather Operations

- **AO1:** ***(High)*** **Addition of X-band real-time downlink.**
  - *Real-time coronagraph data*. Real-time coronagraph data from Firefly is rated as high value for space weather operations owing to the immediate improvement that observations from different vantage points, including the polar orbits, could make to forecast operations and, for example, the arrival time of CME forecasts.
  - *Real-time magnetogram data*. The advantages of having real-time magnetogram data off the Sun–Earth line and out of the ecliptic could show promise for improving models and forecasts but would need to go through a period of intercalibration with the Sun–Earth line magnetograms, development, demonstration, and validation, meaning that improvements would not be immediate.
  - *Real-time EUV data*. Real-time EUV data is rated as medium value to space weather operations owing to the additional situational awareness of solar activity from vantage points off the Sun–Earth line and out of the ecliptic. Use in operations could be achieved in the near future.
  - For a real-time downlink and telemetry augmentation to the Firefly mission, dedicated DSN service—*or some equivalent for dedicated space weather telemetry streams from observatories in deep space*—would need to be made available. Considering the high-demand and limited resources of the DSN, it may be problematic to rely on those ground stations. Furthermore, any Firefly data that would be made available for use in near-real-time analysis and/or modeling would need to properly account for speed-of-light time delay from Firefly in its distant, heliocentric orbits with respect to Earth.
- **AO2:** ***(Low)*** **Soft X-ray intensity measurements.** This could improve current models being tested operationally to support human exploration.
- **AO3:** ***(Low)*** **Particle measurement up to 1 GeV/nuc.** This is important to characterize galactic cosmic rays that have the highest chronic radiation impacts on space exploration systems and astronauts.

E.B.6 Space Weather Contributions from the HELIX Mission Concept

Mission Concept Summary

In their community paper submission to the decadal survey, Szabo et al. (2022) write:

> To determine the inner heliospheric structure and evolution of Interplanetary Coronal Mass Ejections (ICMEs), multi-point, in situ measurements of the magnetic field and solar wind plasma properties are necessary. The same ICME has to be observed simultaneously by at least four spacecraft at different azimuth angles to detect deformations from the

traditional symmetric cylindrical/horse-shoe-shaped geometry. In addition, ICMEs have to be observed at different radial distances from the Sun to detect evolutionary changes. This would require at least two more spacecraft. All six spacecraft would have to be in a 90-degree wedge corresponding to the average angular size of ICMEs. Since orbital mechanics does not allow for such a long-term configuration, a larger spacecraft fleet is needed that would form different 4–6 spacecraft configurations at different times.

The HELIX mission concept was originally developed in the NASA LWS Architecture Study (Cohen et al. 2022) and further studied by the JHU/APL mission design laboratory prior to submission as a community input paper to this decadal survey (Szabo et al. 2022). The HELIX constellation of seven spacecraft envisions a heliocentric orbit via a single launch, with a ~7.5-month orbit periodicity (1:1 resonance with Venus). A Venus encounter occurs after ~0.5 revolution about the Sun (roughly 3.7–5.7 months). A launch in 2032–2033 is assumed with C3 of ≤15 km^2/s^2. Upon arrival at Venus, each spacecraft experiences a Venus gravity assist (VGA) that disperses the constellation into distinct science orbits. A single deterministic Venus spacing maneuver (VSM) is performed for most spacecraft 10–80 days after launch (optimal timing depends on the Venus transfer geometry) to enable a minimum time-spacing between each sequential Venus encounter. A "central" spacecraft in the constellation encounters Venus at the nominal epoch with no VSM required, while the other spacecraft are spaced away from the central spacecraft.

The TRACE process was performed on what was described as the "augmented" mission in the mission community input paper (Szabo et al. 2022). This report evaluates the TRACE mission profile:

On all seven spacecraft:

- Dual magnetometers
- Solar wind plasma and composition instrumentations
- Suprathermal ion and SEP detectors
- Radio waves and solar wind electron detection
- One remote sensing instrument on each spacecraft in the constellation choosing from the following list:
  - Photospheric magnetograph (3 spacecraft only)
  - Heliospheric Imager (3 spacecraft only)
  - EUV imager (1 spacecraft only)

There is no discussion in the HELIX community input paper summary on instrument data rates, or data volumes. The paper mentions that on-board storage of up to 1 week's measurements is anticipated with associated weekly DSN downlinks. An X-band link is mentioned for lower-latency spacecraft housekeeping and orbital maneuver communications.

HELIX is envisioned as a Class C+ mission with an ELV-class launch vehicle (e.g., Falcon, Vulcan, New Glenn), and a 3-year primary mission that will make entirely new in situ measurements of solar wind and CME structure and SEP extent in the inner heliosphere. The remote sensing instrument suite would add the ability to image CMEs and possibly solar wind structures from novel viewpoints in the ecliptic plane upstream of the current or planned Lagrangian point orbit locations.

Space Weather Value of the Mission as Proposed (Table E.B-8)

Value to Space Weather Research

The primary value to space weather research of the HELIX mission as proposed lies in its ability to explore the in situ structure of CMEs and SEP events inside of 1 AU and off the Sun–Earth line, allowing, for the first time, a measurement of space weather-relevant quantities well upstream of Earth. This would increase our understanding of the inner heliospheric conditions and how they influence the acceleration, propagation, and evolution of dynamic space weather phenomena that impact Earth or space missions at other locations in the inner heliosphere. The remote sensing instruments add additional value given the constellation's location off the Sun–Earth line (most of the time) and well inside the Earth–Sun L1 observation point.

TABLE E.B-8 Summary of the HELIX Mission's Potential Value to Space Weather Research and Operations

IDs	Mission Value for SWx	Mission Aspect of Interest	Impact on Research or Operations?	Priority
Mission as Proposed				
PR1	Multipoint CME measurements.	Measurements of CME structure during propagation to 1 AU will inform inner heliosphere space weather models. Very high proposed data latency (1 week) away from the Sun–Earth line prohibits applicability of these data to forecasting or nowcasting operations.	Research	High
PR2	Multipoint SEP measurements.	Longitude and radial dependence and evolution of SEP event properties will inform SEP predictive modeling.	Research	High
PR3	Multipoint solar wind measurements.	In situ measurements of solar wind density, velocity and magnetic field measurements will improve “background” solar wind models through which CMEs and SEPs are propagated.	Research	High
Mission Augmentations				
IDs	Mission Value for SWx	Suggested Augmentation	Impact on Research or Operations?	Priority
AR1	Novel CME, solar wind, and SEP measurement location to provide 3D structure.	Additional (or one of original 7) spacecraft put into inclined orbit to ecliptic via VGA.	Research	Medium
AR2, AO3	Characterization of highest energy SEPs at multiple locations upstream of 1 AU can inform SEP acceleration and transport models.	Increase SEP measurements to 1 GeV/nuc.	Research, Operations	Low
AO1	Solar wind, CME, and SEP measurements, both in situ and imaging upwind of L1 and off Sun–Earth line, complements L1 + L5 measurements to give additional model inputs and/or extended lead-time on Earth-directed events.	Near-real-time X-band beacon downlink.	Operations	High
AO2	Increases value for solar magnetic eruption forecasting.	Chromospheric imaging channel in the EUV imager.	Operations	Low

NOTES: (1) IDs are identification codes used and assigned below; PR: As proposed value to SWx research; PO: As proposed value to SWx operations; AR/AO: same with mission augmentations. (2) The panel used the augmented Remote Sensing instrument suite mission profile for this evaluation. Acronyms are defined in Appendix H.

- **PR1:** ***(High)*** **Simultaneous multipoint CME measurements.**
  - Multipoint CME measurements across a wide spatial domain would provide novel data on the internal structure of CMEs—the root cause progenitors of severe geomagnetic storms. Current data from Heliospheric Imagers on STEREO and Parker Solar Probe show that CMEs are complex, turbulent, plasma structures in which it is clear that density, local velocity, and magnetic field orientation change significantly on spatial scales down to thousands of km. In addition, the shock structure ahead of the driver plasma is complex and its role in accelerating energetic particles to relativistic energies remains unclear. Having simultaneous multipoint measurements of CME shock structure along with SEP measurements will help elucidate how energetic particles are accelerated at different point on the CME shock boundary, potentially leading to new insights on how to forecast which eruption events cause large SEP events.

- **PR2: *(High)* Simultaneous multipoint SEP measurements.**
  - Like the multipoint CME measurements described above, simultaneous multipoint in situ measurements of SEP fluence across a wide spatial domain would greatly increase our understanding of SEP acceleration, seed particle populations, and upstream conditions that are conducive to producing large SEP events. Comparison of upstream and post-shock passage from the various HELIX spacecraft in the inner heliosphere will be useful in characterizing the evolution of SEP events as they propagate outward to Earth and beyond. When the HELIX constellation is in the Sun–Earth line region, these measurements can be compared with measurements from L1, lunar, and geospace instruments to further elucidate how SEP events evolve as they transit the heliosphere, potentially leading to advances in our ability to predict SEP events with sufficient lead time to provide useable warnings to astronauts in interplanetary space or on the Moon or Mars.
- **PR3: *(High)* Simultaneous multipoint solar wind measurements.**
  - These measurements will contribute additional vantage points with which to validate solar wind models. With measurements from positions at smaller solar distances than L1 as well as off the Sun–Earth line, the evolution and spatial structure of the solar wind can be studied in greater detail. Such longitudinal and radial structure is critical for understanding the background solar wind into which CMEs and SEPs propagate which is known to have significant effects on the resulting severity of the associated space weather hazard at/near Earth as well as other locations of interest throughout the heliosphere, including Mars. The multipoint solar wind data would also be of value as assimilative proof-of-concept corrections to solar wind models that could enhance forecast accuracy in the future.

Value to Space Weather Operations

No real-time or near-real-time (NRT) beacon data downlink is planned for the proposed mission in its *current* format. As proposed, the mission is therefore not capable of providing inputs to real-time operations. The nominal prime mission length of 3 years is also too short to accumulate significant statistical information on SEP characteristics over the solar cycle. Thus, the mission as proposed does not offer any potential climatological or benchmarking contributions to space weather applications unless its lifetime is extended to at least one solar cycle. Tangible value to operations in the case of an NRT beacon would accrue from the following mission elements:

Remote sensing:

- NRT solar wind and CME measurements from non-Sun-Earth longitudes and well inside of the L1 point would offer valuable additional measurements to short-term forecasting of incoming space weather events as well as valuable nowcasting data during events to judge duration and All Clear conditions.

In situ:

- NRT multipoint SEP measurements would be of high value to short-term warnings and nowcasts of incoming radiation storms as well as to judge All Clear conditions at the conclusion of the storms.

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

Value to Space Weather Research

- **AR1: *(Medium)* Out-of-ecliptic observations from inclined orbit.**
  - Adding an out-of-ecliptic spacecraft to the HELIX constellation would increase its value to space weather research because currently all measurements of solar wind, CME, and SEPs have been from the ecliptic. Solar Orbiter may achieve out-of-ecliptic measurements in the 2030 timeframe, but given its orbital perihelion radiation exposures, it remains to be seen if it will survive until that point.
- **AR2: *(Low)* Increase SEP measurements to 1 GeV/nuc.**
  - Extending the SEP measurements to 1 GeV/nuc would allow better characterization of not only extreme SEP events (including Ground-level Enhancement events), but also the GCRs in the inner heliosphere. Both of these have impacts on evaluating/designing satellites and planned astronaut activities.

Value to Space Weather Operations

- **AO1: *(High)* Near-Real-Time X-band beacon downlink.**
  - The addition of continuous NRT "beacon" data from HELIX is rated as high value for space weather operations owing to the improvement that observations from different vantage points inside of L1 and off the Sun–Earth line in the ecliptic could make to forecast operations—for example, the arrival time of CME forecasts and measurements of Bz. Beacon data generally consists of lowered spatial and/or temporal resolution image and in situ data that reduce the bit rate of the data stream significantly compared to the full-resolution science data. Particularly for the Bz characterization, HELIX could increase the warning lead time for incoming southward Bz structure, the main driver of severe geomagnetic storms, significantly from its near-Venus orbital region.
- **AO2: *(Low)* Chromospheric imaging channel in the EUV imager.**
  - The inclusion of a solar chromosphere imaging capability in the EUV imager—for example, a He II 304Å channel—would improve the utility of the remote sensing observations for forecasting solar magnetic eruptions. Nonpotential field structures in active regions are often demarcated by trapped plasma in the twisted field lines, also known as "filaments," which can be imaged in chromospheric spectral line emissions such as H-alpha 6563Å or He II 304Å. Obtaining images of active region filaments from off the Sun–Earth line could help detect when these structures begin rising which is often a precursor to eventual eruption. However, this augmentation is rated low because the EUV imager will only be on one spacecraft and may not afford the spatial resolution required to reliably track active region filament evolution.
- **AO3: *(Low)* Increase SEP measurements to 1 GeV/nuc.**
  - This is important to space climate applications in capturing characteristics of the GCRs which have the highest radiation impacts. Furthermore, GCR flux is an important input to all space radiation analysis (SEEs on satellites, radiation shielding studies, astronaut health).

E.B.7 Space Weather Contributions from the Interstellar Probe (ISP) Mission

Mission Concept Summary

Interstellar Probe (ISP) is a Large Strategic Science class mission that proposes to follow-on from the Voyager missions and send an observatory to the outermost edges of the heliosphere and into the pristine interstellar medium—that is, the interstellar medium unaffected by the heliosphere, beyond that explored by the Voyagers. ISP consists of a single observatory, which will launch via a heavy-lifter (e.g., SLS) and employ a Jupiter gravity assist (JGA) to achieve a hyperbolic solar-escape trajectory at an asymptotic velocity of ~7 AU/year. That escape trajectory allows ISP to reach pristine interstellar space at >300 AU within the prime mission lifetime of 50 years. The ISP science payload consists of the following instruments:

- Magnetometer (MAG): 3-axis magnetic field vectors.
- Plasma subsystem (PLS): electrons and ion composition from <3 eV/e to 20 keV/e (where "e" is elementary charge).
- Pick-up ions (PUI): ion composition, including isotopes, with charge state from 0.5–80 keV/e, protons (H) up to iron (Fe).
- Energetic particle subsystem (EPS): electrons and ions with composition from 20 keV to 20 MeV.
- Cosmic ray subsystem (CRS): electrons and ions with composition from 1 MeV/nuc to 1 GeV/nuc.
- Plasma wave subsystem (PWS): 1 Hz to 5 MHz electrostatic and electromagnetic waves.
- Energetic neutral atom camera (ENA): 1 to 100 keV ENAs (baselined hydrogen).
- Interstellar Dust Analyzer (IDA): $1e^{-19}$ to $1e^{-14}$ g, 1–500 amu dust measurements with mass spectroscopic capability.
- Neutral mass spectrometer (NMS): Isotopic mass composition with mass resolution, $\Delta m/m \leq 1$ percent.
- Lyman-alpha spectrograph (LYA).
- Visible/near-IR camera (part of the extended payload for *planetary science* augmentation and education and public outreach).

The proposed concept of operations for ISP stipulates that the observatory will turn on after commissioning following the JGA and will remain on for the entirety of its 50-year prime mission and trajectory outbound throughout the heliosphere and into the interstellar medium. Targeted campaigns with high-rate data collection will be planned for critical events such as crossings of the termination shock and heliopause in the 2050 timeframe. ISP may also opportunistically target small bodies in the Kuiper Belt.

Space Weather Value of the Mission as Proposed (Table E.B-9)

Value to Space Weather Research

Given the mission concept of operations, research into space weather phenomena using ISP will be restricted to the outer planetary regions. This may have some value for understanding the impact of coronal mass ejections on the outer planets and their magnetospheres depending on the planetary fly-by design of the final trajectory. More significantly, the long-term nature of the mission (more than 50 years) implies that the mission may increase our knowledge of space climate by measuring the Anomalous and Galactic Cosmic Ray (ACR and GCR) flux over several solar cycles. Tying these measurements to co-temporal measurements of the solar magnetic field will yield a better understanding of the interplay between solar activity and ACR/GCR flux. Measurements in the hypothesized ACR acceleration region of the outer heliosphere (beyond the heliospheric termination shock at ~84 AU) may also shed some light on the underlying nature and physics of ACR acceleration, which may also prove valuable for future predictive models of radiation levels throughout the heliosphere.

- **PR1:** ***(Low)*** **Long-term cosmic ray observations.** Cosmic Ray Subsystem (CRS) measurements over the 50-year prime mission and including multiple solar cycle variations and the shielded, low-energy population beyond the heliosphere (understanding sources) can be used to develop improved climatological models of ACRs and GCRs as a function of solar activity and heliocentric distance.

Value to Space Weather Operations

The current concept of operations for ISP does not include measurements inside of the orbit of Jupiter. For the foreseeable future, space weather operational forecasting and nowcasting will be restricted to Earth, cislunar, and perhaps Mars space environments. The mission as proposed therefore has no value to space weather operations. However, as noted in the Definition of Terms section of this panel's report, in the larger set of space weather

TABLE E.B-9 Summary of Interstellar Probe's Potential Value to Space Weather Research and Applications

Mission as Proposed				
IDs	Mission Element	Value to Space Weather Research or Applications	Impact on Research or Operations?	Priority
PR1, PA1*	Long-term cosmic ray observations.	Observations required to better understand cosmic ray sources (space climate research) and develop climatological models of galactic cosmic ray fluxes as a function of solar cycle and heliocentric location (applications).	Research, Applications	Low
AA1	Adverse effects of long-term operations in deep space.	Addition of dosimeters and other experiments to study the long-term degradation and adverse effects on spacecraft systems of extended (50 years) operations in deep space.	Research	Low

* "PA" refers to "Proposed Applications value" as contrasted with the "Proposed Operations (PO) value" format of other TRACE missions. Similarly, "AA" refers to "Augmentation to Applications" value. See text below on the value of the mission to space weather operations for an explanation of this distinction.
NOTE: IDs are identification codes used and assigned below; PR: As proposed value to SWx or space climate research; PA: As proposed value to SWx applications; AR/AA: same with mission augmentations.

applications, the long-term GCR observations from the ISP mission are potentially of value to future designers of spacecraft systems or mission planning operations.

- **PA1:** ***(Low)*** **Long-term cosmic ray observations.** Cosmic Ray Subsystem (CRS) measurements over the 50-year prime mission, and including multiple solar cycle variations, may be useful in refining future spacecraft designs and/or mission profiles, particularly in regard to human deep space mission planning and radiation risk assessments.

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

There are no envisioned augmentations to the ISP mission that would enhance its value to space weather research or operations. However, the mission could potentially increase its benefit to space weather *applications*, in particular future deep space vehicle design, by augmenting its payload with a compact dosimeter instrument that would record total ionizing dose information throughout the mission profile as well as experiments to qualify and quantify long-term degradation and adverse effects during decades-long, deep-space operations.

- **AA1:** ***(Low)*** **Long-term effects in deep space.** Strategically located dosimeters to study the long-term degradation and adverse effects of extended (50 years) operations in deep space on specific spacecraft and instrument components.

E.B.8 Evaluation of the Lynx Mission Concept by the SWSA Panel

Mission Concept Summary

Lynx is intended as a mission in the largest-category class (~$2 billion, directed) to revolutionize our understanding of magnetospheric physics and magnetosphere–ionosphere coupling. Lynx is a combination of the Magnetospheric Constellation (MagCon) and the Plasma Acceleration, Reconfiguration, and Aurora Geospace Observation Network (PARAGON) mission concepts. The two mission concepts together combine an extensive constellation of in situ observatories (36 spacecraft in MagCon) with remote sensing observatories (3 spacecraft in PARAGON) to resolve for the first time mesoscale plasma transport and direct connections between in situ magnetospheric activity and structures and auroral activity and features.

The in situ component of Lynx (MagCon) consists of 36 small satellites distributed with 12 each along three different orbits. The three orbits were innovatively designed such that they all precess in local time at the same rate, enabling the constellation to stay together throughout the year (as Earth orbits the Sun) and for the duration of the prime mission. Periapses range from 1.1 to 1.5 R_E geocentric distance, and apoapses range from 8 to 15 R_E geocentric distance. The orbits are low-inclination, enabling observations from in and around the magnetic equatorial plane at low-magnetic-latitudes. All 36 spacecraft can be launched via the same launch vehicle (LV), because the observatories were designed to integrate to the LV using ESPA rings, which can be stacked one on top of another (i.e., 12 spacecraft per ESPA ring and a stack of 3 ESPA rings within the LV fairing). Each of the 36 in situ observatories incorporate a common payload of three instruments:

- Electrostatic analyzer (ESA) for in situ plasma distributions and moments
- Solid state telescopes (SSTs) for in situ energetic particle distributions
- Fluxgate magnetometer (FGM) for in situ magnetic field (DC to low-frequency waves)

The remote sensing component of Lynx (PARAGON) consists of 3 spacecraft spaced evenly (120 degrees apart in true anomaly) along a common, circular orbit of radius 9 R_E (geocentric). These observatories offer continuous observations of magnetospheric energetic neutral atom (ENA) images, extreme ultraviolet (EUV) imaging of the plasmasphere, and far ultraviolet (FUV) and optical imaging of the auroral ovals in both polar hemispheres simultaneously. Each of the 3 remote sensing observatories incorporate a common payload of five instruments:

- ENA Narrow Angle Camera (ENA-NAC) for unprecedented spatial resolution in ENA imaging of magnetospheric plasma.
- ENA Wide Angle Camera (ENA-WAC) for global scale imaging of magnetospheric plasma.
- EUV imager for plasmaspheric imaging.
- FUV imager for high-resolution, global auroral imaging (day and nightside).
- Optical imager for high-resolution, global auroral imaging (nightside only).

By combining the PARAGON and MagCon concepts, Lynx promises to provide the revolutionary and unprecedented strategically distributed-multipoint, high-resolution, in situ and remote sensing observations necessary to resolve major outstanding questions in magnetospheric physics. Those outstanding questions to be addressed are fundamental to planetary magnetospheric plasma physics and concern the nature of mesoscale (i.e., between ion kinetic scales at <~1,000 km and global scales at ≥10 R_E) processes critical to substorm and storm-time activity, global magnetospheric convection and energy and mass transport, and magnetosphere–ionosphere coupling.

Space Weather Value of the Mission as Proposed (Table E.B-10)

Value to Space Weather Research

The benefits of the Lynx mission as proposed are extensive concerning space weather in Geospace. Even without a low-latency, continuous data link to ground for real-time space weather relevant telemetry streaming (see priorities below), the Lynx constellation will still provide critical observations directly relevant to multiple space weather environmental hazards in Geospace, particularly: auroral activity and intense current systems, substorm activity and spacecraft charging conditions, ring current evolution and geomagnetic storm activity, and radiation belt variability and radiation threats to human systems.

- **PR1:** ***(Medium to High)*** **Lynx remote sensing observatories can provide observations of the auroral activity in both hemispheres simultaneously.** Lynx observations and data will enable studies of what auroral features map back to magnetospheric processes and structures (i.e., they show up similarly in both hemispheres simultaneously) versus what auroral features are the result of local ionospheric processes (i.e., they show up in only one hemisphere), which is important information tracing to the development of improved models of auroral activity and related space weather effects and hazards. Auroral activity has been related to spacecraft surface charging hazards in the LEO environment (High priority), and the enhanced current systems associated with auroral activity can drive ground-induced currents (GICs) that pose a threat to power grid infrastructure (Medium priority). Space weather research may also benefit from studies using Lynx auroral observations to link auroral activity to the satellite charging environment in LEO or predictions of GIC conditions affecting the power grid.
    - Note: There is a new, advantageous aspect here considering coordination with geomagnetically induced current (GIC) and ground electric field (GEF) monitoring networks that were unavailable during the Polar and IMAGE mission eras.
- **PR2:** ***(Low to High)*** **Lynx all together (in situ and remote sensing observatories) can provide observations of the energetic particle injection and localized flow burst environment in and around MEO, GEO, and low-latitude HEO.** Resolving and characterizing "mesoscale" (i.e., between ion kinetic, ~10^3 km, and global MHD, ~10^5 km, scales in Earth's magnetotail) plasma structures and dynamics in Earth's magnetotail plasma sheet and inner magnetosphere is a major science objective of Lynx. Such dynamics include substorm activity like auroral enhancements, energetic particle injections, and fast (hundreds of km/s), localized flow bursts of hot plasma. Particle injections and plasma flow bursts are known to be important for and connected to internal (Low priority) and surface (High priority) spacecraft charging events and hazards. In particular, Lynx will enable space weather research important for developing

TABLE E.B-10 Summary of Lynx's Potential Value to Space Weather Research and Operations

IDs	Mission Value for SWx	Mission Aspect of Interest	Impact on Research or Operations?	Priority
Mission as Proposed				
PR3 and PO1	Space radiation environment throughout Earth's radiation belts.	36× in situ observatories with energetic particle detectors and orbits spanning the electron radiation belts at low latitudes.	Research and Operations	Medium
PR1 and PR2	Satellite charging environment.	Observations required to improve and refine models of satellite charging environments throughout LEO (remote sensing spacecraft auroral imaging; PR1), MEO, GEO, and HEO (in situ spacecraft; PR2).	Research	Surface Charging: High Internal Charging: Low
PR1	Ground-induced currents (GICs) and impacts on power grid infrastructure.	Observations of the full auroral ovals in both hemispheres provides observations relevant to intense ionospheric current systems and GICs; new aspect here considering GIC/GEF networks that were unavailable during Polar and IMAGE eras.	Research	Medium
Mission Augmentations				
IDs	Mission Value for SWx	Suggested Augmentation	Impact on Research or Operations?	Priority
AO1	Developing a continuous, low-latency SWx telemetry relay network.	3× Lynx remote sensing spacecraft provide continuous comm link over North America and an accessible relay network for SWx telemetry streams throughout geospace.	Operations	High
AO2	Near-real-time auroral activity in full ovals in both hemispheres.	Real-time telemetry stream.	Operations	High
AO2 and AO3	Space situational awareness of satellite charging environments throughout LEO, MEO, GEO, and HEO.	Real-time telemetry stream.	Operations	High
AO4	Space situational awareness of space radiation environment throughout Earth's radiation belts.	Real-time telemetry stream.	Operations	Medium
AR1	Relating observed satellite charging environment to actual charging/discharge events.	Add spacecraft charging sensors (e.g., charge-discharge monitors) on all Lynx spacecraft.	Research	High

NOTES: IDs are identification codes used and assigned below; PR: As proposed value to SWx research; PO: As proposed value to SWx operations; AR/AO: same with mission augmentations. Acronyms are defined in Appendix H.

conditional probabilistic nowcast/forecast models of the spacecraft charging environment in MEO, GEO, and HEO. Lynx observations will also provide data relevant to hindcasting and reanalysis modeling that can be used for spacecraft anomaly resolution.

- Note: Simultaneous measurements enable development of low-to-high and high-to-low altitude models like SHELLS/PreMeVE, that allow us to fill in when we only have data from one location or the other.

- **PR3:** ***(Medium)*** **Lynx in situ observatories can provide observations of the radiation belts nearly continuously.** Earth's radiation belts are an environmental hazard for robotic and crewed spacecraft and astronauts. The intensity and extent of the electron radiation belts are especially variable and difficult to predict. Frequent (≥1/hour) measurements of the radial distributions of radiation belt electron intensities (100 keV to several MeV) between ~1.1 R_E and ~8.0 R_E (geocentric distances) from low magnetic latitudes are required for characterizing the state of the electron radiation belts and their activity-dependent variability.

  - Note that for Lynx, such observations of Earth's radiation belt electrons will drive requirements on SST performance and functionality considering background contamination, species differentiation, instrument dynamic ranges and sensitivity, and energy and angular ranges.

Value to Space Weather Operations

No real-time downlink is planned for the proposed mission in its *current* format. *As proposed,* the mission is therefore not capable of providing inputs to real-time nowcasting or forecasting operations. However, observations of the radiation and auroral environments can be used for development of benchmarks and as inputs for climatological models (e.g., IRENE radiation belt model), which engineers use routinely for space situational awareness, anomaly resolution, risk mitigation, and design constraints for satellite missions.

- **PO1:** ***(Medium)*** **Lynx in situ observatories can provide observations of the radiation belts nearly continuously.** Such observations (see more details on observational ranges above) are critical for developing benchmarks and climatological models plus space situational awareness and hindcasting models for satellite risk mitigation and anomaly resolution.

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

Value to Space Weather Research

- **AR1:** ***(High)*** **Addition of charge/discharge and radiation environment sensors on all spacecraft.** Lynx orbits (both in situ and remote sensing observatories) transit multiple regions of concern for spacecraft charging hazards. Considering this, spacecraft charging data—such as charge/discharge sensors, electron intensities in the keV to 100s keV range, and/or spacecraft potential monitoring—would prove valuable for space weather research.

Value to Space Weather Operations

The benefits of an augmented Lynx mission to space weather operations are direct and clear. With the addition of a low-latency, continuous data link to ground for real-time space weather relevant telemetry streaming (see priorities below), the Lynx constellation could provide critical observations covering multiple space weather environmental hazards in Geospace, particularly: auroral activity and intense current systems, substorm activity and spacecraft charging conditions, ring current evolution and geomagnetic storm activity, and radiation belt variability and radiation threats to human systems.

- **AO1:** ***(High)*** **Lynx can provide a communications relay network for continuous, low-latency (near-real-time) space weather data beaconing.**
  - 3× remote sensing spacecraft ensure continuous coverage over the northern hemisphere, enabling continuous communications with a high-latitude station (e.g., in Alaska).
  - Remote sensing spacecraft are all 3-axis stabilized, making for straightforward approach to alignment/design of receiving antennas (for data streams incoming from in situ spacecraft and other space weather assets) and transceivers (for cross-link with each of the other two spacecraft and comm-link to ground).
  - Relay network can be used for Lynx RT stream *and* other (future) space weather assets in geospace.
  - Need to account for this up-front in the requirements and design of the telemetry budget and comm systems on the PARAGON spacecraft.
  - Consider this aspect for descope options on Lynx as a whole; all three PARAGON spacecraft would be needed to make this real-time relay network possible.

- ○ Potential for additional value and investment return via “Emerging Opportunities”: Laser communication cross-link (between 3 spacecraft) and downlink (each spacecraft to ground) could enable exceptional telemetry rates.

Remote sensing observatories: With the augmentation of a low-latency, continuous data link, the mission would provide full auroral oval monitoring in both hemispheres with the FUV and optical imagers and provide remote sensing observations of energetic particle injections from the magnetotail into the inner magnetosphere (including through GEO). Both of these are of high value from an operational space weather perspective.

- **AO2:** ***(High)*** **Lynx can provide simultaneous auroral observations in both hemispheres.** Such data are valuable for
  - ○ Nowcast and hindcast capabilities concerning anomaly attribution and resolution informed by environmental conditions for spacecraft charging at LEO.
  - ○ Nowcast capabilities concerning ionospheric current systems, GICs and power grid effects.
  - ○ Nowcast capabilities concerning societal-interest and commercial value for auroral oval/sightings prediction.
- **AO3:** ***(High)*** **Lynx can provide global observations of energetic particle injections plus localized and intense plasma flow bursts (spacecraft charging hazards at MEO, GEO, and HEO) from the magnetotail into the inner magnetosphere.** Such data are valuable for improved benchmarking and climatological model development enabling systems’ risk mitigation through improved resilient design plus nowcast and hindcast capabilities for anomaly attribution and resolution concerning:
  - ○ Storm-time ring current evolution, GICs, and power grid effects.
  - ○ Space situational awareness (nowcast and hindcast) environmental conditions for spacecraft charging at MEO/GEO/HEO.

In situ observatories: The planned in situ observatory orbits will result in the spacecraft collectively spending large amounts of time (potentially continuously with at least one of the 36 spacecraft) in Earth’s radiation belts. With the augmentation of a low-latency, continuous data link and adequate instrument requirements for the energetic particle instruments, Lynx could provide near-continuous monitoring of radiation belt intensities throughout the inner magnetosphere.

- **AO4:** ***(Medium)*** **Lynx can provide near-continuous observations of the variable intensity of Earth’s radiation belts.** Such data are valuable for improved benchmarking and risk mitigation through climatological model development plus nowcast and hindcast capabilities for satellite anomaly attribution and resolution concerning:
  - ○ Spacecraft charging.
  - ○ Total ionizing and nonionizing dose.
  - ○ Single event effects.

Achieving such monitoring drives performance and functionality requirements on the in situ SST instruments to enable these radiation belt measurements effectively considering background contamination, species differentiation, instrument dynamic ranges and sensitivity, and energy and angular ranges.

E.B.9 Space Weather Contributions from the Concept OHMIC Mission

Mission Concept Summary

The Observatory for Heteroscale Magnetosphere–Ionosphere Coupling (OHMIC) mission is a constellation of four spacecraft, 2× in situ and 2× imagers, targeting the auroral acceleration region (AAR) to determine how electromagnetic energy is converted into (charged) particle kinetic energy in Earth’s magnetosphere–ionosphere system. OHMIC is proposed as a large-scale mission suitable for the current STP or LWS programs. The observatories combine global and local, high-resolution auroral imaging (UV wavelengths) with multipoint, in situ measurements of the local plasma, field, and wave conditions within the AAR to determine magnetospheric energy inputs and resultant heating and acceleration of ionospheric plasma, including ion outflow from the ionosphere back into the magnetosphere, an inherent systems-coupling process. The OHMIC mission can be implemented within 5 years, including Phase A.

The OHMIC constellation includes the following:

- Two spinning, in situ instrumented observatories ("Mother" and "Daughter").
  - In the following orbits:
  - Mother: 500 km perigee × 6,000 km apogee (altitudes), 90-degree inclination, 160-minute orbit period.
  - Daughter: 1,000 km perigee × 5,500 km apogee (altitudes), 90-degree inclination, 160-minute orbit period.
  - And both with the following, identical scientific payload:
  - Auroral Plasma Instrument (API)—3D electron and ion distributions in energy from 1 eV–40 keV, with composition and angular resolution (i.e., pitch angle distributions).
  - Electromagnetic Fields Instrument (EFI)—3D electric and magnetic fields and waves, DC to 1 MHz (with fluxgate magnetometer, search-coil magnetometer, and 2× axial + 4× wire (spin plane) E-field booms), plus plasma density (Langmuir probe).
- Two 3-axis stabilized, imaging observatories ("Imaging-H" and "Imaging-L").
  - In the following orbits:
  - Imaging-L: 500 km perigee × 6,000 km apogee, 90-degree inclination, 160-minute orbit period.
  - Imaging-H: 500 km perigee × 43,800 km apogee, 90-degree inclination, 800-minute orbit period (5× others' periods; FOV from apogee covers full hemisphere of Earth).
  - And both with the following, identical scientific payload:
  - UVI–UV Imager LBHT (140–180 nm) and LBHL (160–180 nm), 8 degrees FOV, 0.03 degree angular resolution.

The Mother and Daughter in situ observatories provide detailed information on ionospheric outflow and magnetospheric energy inputs within the AAR. The Mother and Daughter are intentionally phased at different altitudes to provide simultaneous multipoint observations at two points along the same magnetic field lines.

Imaging-L and -H provide high-resolution, localized (-L) and global (-H) images of auroral activity, through which the Mother and Daughter observatories are measuring in situ plasma conditions.

Space Weather Value of the Mission as Proposed (Table E.B-11)

Value to Space Weather Research

As many of the sensors envisioned for OHMIC have past analogs, OHMIC provides new opportunities through simultaneous complementary measurement of relevant parameters, compared to past missions which had a sparser system of observations. Such observations contribute to knowledge of the state and evolution of the ionosphere–thermosphere system, particularly through the dynamic auroral zone and high latitudes, where spacecraft charging also represents a considerable space weather hazard.

- **PR1:** ***(High)*** **In situ plasma.** Hot electron plasma (~10 keV) causes surface charging and its altitude structure is not well known. Charging hazard may be particularly intense through the high-latitude auroral zone. Improved surface charging plasma climatology models contribute to more efficient, robust spacecraft designs. Pertains to OHMIC observatories Mother and Daughter, as proposed
- **PR2:** ***(Medium)*** **Vector magnetic field data** fills in some important spatial gaps. These data could readily be incorporated into empirical magnetic field models that are sometimes used operationally. The data could also be used for data assimilation and (in LEO) to constrain locations of FACs and electrojets (AMPERE). Pertains to OHMIC Mother/Daughter observatories.

TABLE E.B-11 Summary of OHMIC's Potential Value to Space Weather Research and Operations

IDs	Mission Value for SWx	Mission Aspect of Interest	Impact on Research or Operations?	Priority
Mission as Proposed				
PR1, PO1	Satellite charging environment.	Observations required to improve models of satellite charging environments throughout geospace.	Research and Operations	Research: High Operations: Medium
PR2 PR3, PO1	Auroral impacts: Ground-induced currents, clutter, scintillation. magnetospheric, ionospheric, and thermospheric states.	Observations of low-altitude electromagnetic fields constrain auroral dynamics. Magnetospheric fields affect mapping, connectivity, transport.	Research	Medium
Mission Augmentations				
IDs	Mission Value for SWx	Suggested Augmentation	Impact on Research or Operations?	Priority
AR3, AO1	Space radiation in multiple unusual orbits for radiation environment characterization.	Proton radiation sensors on all spacecraft, real-time telemetry; solar energetic particles are additional, nonnegligible energy input into the ionosphere–thermosphere system.	Research and Operations	LEO/real time: High Imaging-H: Low
AR2, AO1	Near-real-time auroral activity in full oval in one hemisphere.	FUV/X-ray imagers, real-time data stream.	Research and Operations	FUV: Medium X-ray: Low Real time: High
AR1, AR5, AR6, AO1	Space situational awareness of satellite charging environments throughout LEO, MEO, GEO, and HEO.	Near-real-time cold plasma (remote via GNSS), hot electrons (in situ), and internal charging (in situ) sensors; energetic electrons are additional, nonnegligible energy input into the ionosphere–thermosphere system.	Research and Operations	Research: Medium, Real time: High
AR1, AO1	Satellite drag environment.	Precision orbit determination (via GNSS sensors added to all spacecraft) for thermospheric density estimates.	Research and Operations	Research: Medium, Real time: High
AR4	Relating observed satellite charging environment to actual charging/discharge events.	Add spacecraft charging sensors (e.g., charge-discharge monitors) on all spacecraft.	Research	High

NOTES: IDs are identification codes used and assigned below; PR: As proposed value to SWx research; PO: As proposed value to SWx operations; AR/AO: same with mission augmentations. Acronyms are defined in Appendix H.

- **PR3:** ***(Medium)*** **Vector electric field** measurements are used to constrain the polar cap potential and auroral convection, and can be used to improve empirical models which are then used by numerical simulations to improve representation of global magnetic and plasma configuration. Pertains to OHMIC Mother/Daughter observatories.

Value to Space Weather Operations

No real-time downlink is planned for the proposed mission in its *current* format. As proposed, the mission is therefore not capable of providing inputs to real-time operations, but as noted below OHMIC data can still be used for satellite operations, *in those cases where data are still valuable up to 1–2 days after the fact*.

- **PO1:** ***(Medium)*** **Satellite anomaly resolution.** For many satellite operators, anomaly resolution or forensics is the higher priority over forecast and nowcast. While anomaly triage can begin almost immediately after an event is detected, data coming in up to *~2 days* after an anomaly can contribute to a decision to return a vehicle to operations. OHMIC measurements that can contribute to this include suprathermal electron distributions and current systems at low altitudes, plasma density at medium and high altitudes, and auroral imagery. This pertains to all four OHMIC observatories. (*Medium* owing to lack of real-time link.)

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

Value to Space Weather Research

Several possibilities exist for augmentations to OHMIC that would extend past data sets. These additional sensors could enable us to learn how to process and exploit their data in real time, and they could be used in scientific studies and AI/ML models benefiting from the more extensive context data provided by OHMIC itself and by the modern heliophysics observation system.

- **AR1:** ***(Medium)*** **Add (new) high-precision GNSS receiver on all vehicles.**
  - Requires achieving <~1 TECU (challenging new accuracy leads to *Medium* rating).
  - On Mother, Daughter, and Imaging-L spacecraft, precision GNSS orbit data can be used to infer thermospheric density from precision orbit determination during perigee passes.
- **AR2:** ***(Low)*** **Add X-ray imager to Imaging-H.**
  - X-rays are slightly more relevant for surface charging than UV.
  - Higher altitude complicates achieving valuable resolution.
  - Prior analog: Polar PIXIE.
  - Also consider including a visible imager (or higher luminosity bands) could enable higher-resolution and more detailed auroral images and data content (see community input papers by M. Henderson on need for better global auroral images and J. Rodriguez on continuous auroral imaging in FUV).
- **AR3:** ***(High and Low)*** **Add ~1–100 MeV proton sensors to Mother, Daughter, and Imaging-L (LEO) and Imaging-H.**
  - Mother, Daughter, Imaging-L: As noted earlier, LEO rated *High* because low-altitude gradients and their solar cycle variation are one of the largest uncertainties in satellite design (climatology) models.
  - Imaging-H provides SEP observations at high L-shells and outside of the magnetopause and at high magnetospheric altitudes, backs up GOES, and aids intercalibration. (*Low* because to first order gives same answers as GOES and other high-altitude platforms.)
  - Prior analog: SAMPEX PET (low altitude <600 km), RBSP/ECT (high altitude).
- **AR4:** ***(High)*** **Add charge/discharge sensors to all observatories.**
  - OHMIC orbits (both in situ and remote sensing observatories) transit multiple regions of concern for spacecraft charging hazards. Considering this, spacecraft charging data—such as charge/discharge sensors, and/or spacecraft potential monitoring—would prove valuable for space weather research. There is no flight history of surface charging/discharge sensor in LEO, and a spinner is especially helpful to learn about attitude/illumination effects on surface charging phenomena.
  - Comparing spinner (Mother) and 3-axis stable (Imaging-L) in a common orbit would be a new and potentially quite illuminating experiment.
  - Prior analog: SCATHA (high-altitude spinner), CRRES (GTO spinner).
- **AR5:** ***(Medium)*** **Add API Electrons to Imager-H and Imager-L.**
  - Nominal energy rage 1 eV to 40 keV.
  - Adding in situ plasma with charging/discharge sensors could raise this *High* owing to the ability to correlate.
- **AR6:** ***(Medium)*** **Add 40 keV to 5 MeV electron sensors to all observatories.**
  - Nominal energy range 40 keV to 5 MeV.
  - Since RBSP, we have learned that we can map radiation measurements from LEO to high altitudes and specify high-altitude electron hazards (SHELLS, PreMeVE). These models were trained on POES/MetOp SEM-2 and RBSP data. However, the era of the SEM-2 workhorse is coming to an end, and will be replaced with some combination of USSF/REACH and MetOp-SG/NGRM. This change in input

observations will require retraining the empirical models. Adding these sensors in the OHMIC orbits will provide both the low- and high-altitude measurements and facilitate retraining the empirical models.
- Furthermore, the eccentric LEO Mother, Daughter, and Imaging-L platforms provide a unique opportunity to map the altitude gradients and solar cycle variability in the LEO radiation environment, which has only been measured at fixed altitudes and/or with limited sensor capabilities. LEO altitude gradients are one of the largest uncertainties in the AE9/AP9-IRENE climatology models used for satellite designs. The spinners (Mother and Daughter) make this even more valuable, as they provide information about altitude gradients along the local field line.
- Prior analog: RBSP.

Value to Space Weather Operations

- **AO1: *(High)* Addition of real-time downlink for space weather relevant data beacons.**
  - Near-real-time plasmasphere images every ~1 hour would be useful for mapping where the surface charging *is not present* and would apply to all high-altitude satellites. For polar vantage points, little modeling is required to interpret this. This type of All Clear indicator was highly valued by users according to the ABT report "Social and Economic Impacts of Space Weather in the United States." (Conversely, single-point or few-point in situ surface charging measurements—hot electrons—are typically only useful to the host vehicle or others flying very nearby, maybe ~0.1 R_E, so that is not a real-time priority.)
  - Near-real-time space-to-space TEC would also be useful if downlinked within ~1 hour, and TEC resolution is better than ~1 TEC unit. Requires real-time ingestion into an assimilative plasmasphere model.
  - Near-real-time magnetometer and electron velocity distributions from Mother and Daughter could help identify FACs and electrojets. Real-time magnetometer data from Mother and Daughter provide some value in constraining global magnetic field models, which can be used for mapping hazards around the magnetosphere and constraining data assimilative space weather models.
  - Near-real-time UV or X-ray imagery would allow development/demonstration of real-time auroral products (including electron surface charging).
  - Details on ionospheric density distributions and mass content in real time were identified as gaps in the NASA Gap Analysis report; OHMIC Mother and Daughter observations could be used to partially fill these gaps if data were available in real time.
  - Precision GNSS orbit determination in LEO can contribute to satellite drag and thermospheric density estimation and situational awareness.
  - With the addition of energetic proton sensors, near-real-time proton radiation gradients provide data valuable to knowing the radiation altitude gradients in South Atlantic Anomaly. This is a specific issue for low-altitude operations, but does not typically require minutes' latency, but hours-day. These data can also supplement geomagnetic cutoff (solar particle access) assessments, which applies to LEO, MEO, and launch.
  - Note, potential technology development effort could include "solar blinding" of UV imagers.

E.B.9 Evaluation of the Resolve Mission Concept by the SWSA Panel

Mission Concept Summary

The Resolve concept entails a fleet of 72 sensors in a dense, global LEO network providing neutral atmosphere information at combined spatial and temporal resolutions never-before captured (e.g., daily and hourly variations on longitudinal scales of the order 1,500 km). Resolve proposes utilizing either commercial constellations and/or fleets of scientific CubeSats to carry newly enhanced (e.g., miniaturized) THz Limb Sounders providing altitude profiles of wind, temperature, and neutral density. Resolve will provide a global network of limb observations, for which there are various options available such as leveraging opportunistic commercial collaborations and/or combined commercial flights with dedicated science CubeSat launches. At its core, and to achieve the required spatial resolution, and revisit time, Resolve will need a LEO constellation configuration similar to the following:

- 18 satellite platforms, each with four THz Limb Sounders in four look directions, equally spaced on 6 orbital planes with an inclination of 80 degrees; or
- 36 satellite platforms, each with two THz Limb Sounders in two look directions, in a similar orbital configuration; or
- 72 satellite platforms each with a single Limb Sounder, again in a similar orbital configuration.

The ultimate goal of the mission is to create a LEO sensor network that can reconstruct the global, time evolving properties of the upper atmosphere important for energy and momentum transport in the coupled lower, middle and upper atmospheric systems.

Space Weather Value of the Mission as Proposed (Table E.B-12)

Global specification of neutral winds, temperature and density have significant value to space weather science, as well as potential to enhance key operational applications. Furthermore, the nature of the mission and its philosophy to leverage opportunistic commercial flights has the ability to create a long-term, and potentially sustainable network of measurements that can be augmented and/or expanded based on availability of platforms and industry collaborations.

Value to Space Weather Research

- **PR1:** ***(High)*** **Neutral density measurements** of the caliber provided by Resolve will dramatically enhance information about spatial and temporal scales of thermospheric density variations and enable key science in ionosphere–thermosphere coupling. The range of scales (spatial and temporal) targeted by Resolve have

TABLE E.B-12 Summary of Resolve's Potential Value to Space Weather Research and Operations

IDs	Mission Value for SWx	Mission Aspect of Interest	Impact on Research or Operations?	Priority
Mission as Proposed				
PR1 and PO1	Characterization of thermospheric neutral density.	Low-latency, multipoint measurements of thermospheric neutral density.	Research and Operations	High
PR2	Characterization of thermospheric neutral winds and temperatures.	Spatial scale sufficient to advance understanding of thermospheric gradients and coupling in ITM system.	Research	High
Mission Augmentations				
IDs	Mission Value for SWx	Suggested Augmentation	Impact on Research or Operations?	Priority
AR1 and AO1	Understanding and improved modeling of coupled upper atmosphere and ionosphere.	GNSS RO profiling and POD data from each vehicle.	Research and Operations	High
AR2, AR3, and AR4	Radiation and charging environments at LEO and energetic particle precipitation impacting the ionosphere/thermosphere system.	If able considering strict mass restrictions on the mission as proposed: Add energetic electron (10s keV to MeV electrons, SEP ions) and charge/discharge sensors to each observatory.	Research	High
AO2	Real-time nowcasting and forecasting inputs.	Add real-time downlink of SWx-relevant data.	Operations	High

NOTES: IDs are identification codes used and assigned below; PR: As proposed value to SWx research; PO: As proposed value to SWx operations; AR/AO: same with mission augmentations. Acronyms are defined in Appendix H.

not been directly observed and would be transformational to studies of multiscale coupling and drivers within the ITM system. Measurements of this caliber would also support coupled model development for both the MIT, and ITM communities, enabling among other things, studies/quantification of driver impacts (atmospheric and magnetospheric) on satellite drag.

- **PR2:** ***(High)*** **Neutral wind and temperature measurements** are key to models of the coupled ionosphere–atmosphere system. For example, these parameters are necessary to understand the conditions under which lower-atmospheric processes can drive the thermospheric state (forcing from below) and under what conditions magnetospheric/ionospheric processes can drive thermospheric state (forcing from above), and the multiscale coupling between the two. Resolve measurements of the winds and temperature will directly enable advancement of these topics by supplying data at a combined temporal and spatial resolution not sampled before. This will have value for space weather research via enhancing the physics of whole atmosphere models.

Value to Space Weather Operations

- **PO1:** ***(High)*** **Neutral density measurements** are operationally important for resident space object tracking, specifically the propagation and prediction of orbital elements for collision assessments. Current operational models, such as NRLMSISE, are semi-empirical relying on relatively simple algorithms and are climatological in nature. Resolve will provide a global network of homogeneous Limb Sounders with the potential of integrating this information into a single product, namely a low-latency, altitude resolved, global specification of neutral densities. If combined with appropriate model development (see Space Weather Science), these measurements would be a tangible step forward for operational models, adding a significant global, data-driven augmentation to satellite drag calculations, a capacity that is not currently available.

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

Value to Space Weather Research

- **AR1:** ***(High)*** **Add dual-band high-precision GNSS receivers on all vehicles.** This would enable both low-noise GNSS radio occultation (RO) measurements as well as precision orbit determination (POD) data acquisition from the mission. Such measurements are a strategic fit to augment the information from THz Limb sounders. Specifically, GNSS RO height resolved measurements of temperature, pressure, and water vapor will be of value to neutral thermosphere modeling efforts. The altitude range of these measurements complement the Resolve THz imaging limb profiles. Similarly, in situ density estimates from vehicle accelerations inferred from the POD data will be a significant complement to the THz and RO limb soundings. Having them on the same platform will afford a unified data set for thermospheric model development. In addition, RO profiles can provide absolute total electron content (TEC) and ionospheric scintillation (s4 amplitude) that would support the development of ionospheric impact models and research into ITM impacts on for example, GNSS PNT systems and HF communications.

The following augmentations would likely require spacecraft design modifications to accommodate higher payload mass. However, the Resolve orbits would be ideal for these measurements so their inclusion would greatly enhance the value of the mission to space weather research and operations.

- **AR2:** ***(Medium)*** **Add 40 keV to 5 MeV electron sensors on all vehicles.** Since RBSP, we have learned that we can map radiation measurements from LEO to high altitudes and specify high-altitude electron hazards (SHELLS, PreMeVE). These models were trained on POES/MetOp SEM-2 and RBSP data. However, the era of the SEM-2 workhorse is coming to an end, and will be replaced with some combination of USSF/REACH and MetOp-SG/NGRM. This change in input observations will require retraining the empirical models. Adding these sensors in the Resolve orbits will provide both the low- and high-altitude measurements and facilitate retraining the empirical models.

- **AR3:** ***(High)*** **Add charge/discharge sensors on all vehicles.** Resolve orbits transit regions of concern for spacecraft charging hazards. Considering this, spacecraft charging data—such as charge/discharge sensors, and/or spacecraft potential monitoring—would prove valuable for space weather hazards research. There is no flight history of surface charging/discharge sensor in LEO.
- **AR4:** ***(High)*** **Add ~1–100 MeV proton sensors on all vehicles.** Low-altitude proton gradients and their solar cycle variation are one of the largest uncertainties in climatology models of the orbital space environment. The addition of these sensors would aid in developing long-term environment models that would benefit the LEO satellite design knowledge base.

Value to Space Weather Operations

- **AO1:** ***(High)*** **Add dual-band high-precision GNSS receivers on all vehicles.** This would enable both low-noise GNSS radio occultation (RO) measurements as well as precision orbit determination (POD) data acquisition from the mission. Such measurements are theoretically readily integrated with other RO measurements (e.g., Spire and COSMIC-2) to provide data assimilation inputs to operational tropospheric/stratospheric and upper atmospheric/ionospheric forecasting models. Augmentation of Resolve with RO would provide significant enhancement to the data (number of RO profiles/day) available for assimilative, operational models of the fully coupled atmospheric system. RO measurements can be inverted to provide TEC profiles in the ionosphere which could contribute to operational nowcasting assessments of ionospheric conditions for RF communications, over-the-horizon radars, and GNSS reception. With low-latency data retrieval, and a large number of spacecraft (depending on configuration) there is the possibility to provide key data that will enhance ionospheric nowcasting information for space weather operations.
- **AO2:** ***(High)*** **Addition of a real-time downlink** system for the constellation. Given the proposed CubeSat format and the large number of spacecraft in the Resolve constellation, this would be a demanding augmentation that would entail both compact antenna technology, higher spacecraft power budgets, and an extensive ground station network with high-throughput connections to operational space weather forecasting offices. Nevertheless, the ability to incorporate Resolve's thermospheric neutral density observations and any additional ionospheric observations into operational nowcasting and forecasting of the LEO orbital environment would have great value to government and commercial satellite operations.

E.B.10 Space Weather Contributions from the SOLARIS Mission Concept

Mission Concept Summary

SOLARIS is intended as a "Discovery-class" (i.e., $500 million to $1 billion, PI-led) mission to rapidly deploy and study the solar polar regions while Parker Solar Probe and Solar Orbiter are both still operational. SOLARIS will provide imaging of the solar disk and in situ solar wind observations from up to 75 degrees solar latitude. Mission lifetime is ~10 years, and it achieves multiple solar polar passes using a trajectory employing one Jupiter Gravitational Assist (JGA) and multiple gravity assists from flybys of Venus. SOLARIS's payload includes

- Compact Doppler magnetograph: Magnetograms and Dopplergrams of the solar disk.
- EUV Imager: Solar disk and coronal structure out to >3.0 solar radii.
- White Light Coronagraph: Coronal observations from 2.5 to >15 solar radii, overlapping with EUV images.
- Magnetometer: Interplanetary magnetic field vector.
- Ion-Electron Spectrometer: Solar wind electrons and ion distributions and moments.
- Fast Imaging Plasma Spectrometer: Composition and kinetic properties of solar wind heavy ions.

SOLARIS is a single spacecraft that is launched in a direct insertion transfer orbit for a JGA maneuver that will raise the heliocentric orbit's inclination to 75 degrees. After that JGA, a series of Venus gravity assists (flybys) will reduce the aphelion of the orbit to a period of ~3 years, enabling two, 3-month solar polar passes per orbit (i.e., one polar pass every 1.5 years).

Space Weather Value of the Mission as Proposed (Table E.B-13)

Value to Space Weather Research

The primary value of SOLARIS lies in space weather research that will reveal polar fields and their impacts on solar wind propagation. Photospheric B-field (magnetograms), Dopplergrams, EUV over full disk, and white light coronagraph data out to >15 $R_\odot$ are all critical space weather observations for space weather research and discovery, as well as proof-of-concept modeling, particularly from the solar polar regions during portions of the orbit, which will significantly supplement observations from Earth (GOES CCOR), L1 (SWFO-L1), STEREO-A, and L5 (Vigil). When not over the poles, SOLARIS data of the solar disk from a vantage point off the Sun–Earth line are still valuable from a space weather perspective.

- **PR01:** ***(High)*** **Remote sensing of polar magnetic fields from magnetogram measurements** is crucial for improved solar wind modeling, which currently has to make assumptions about the polar magnetic field. Observations enable better knowledge of active regions over one full hemisphere of the Sun, impossible to determine from the Earth-Sun line alone. For SOLARIS, polar field measurements will not be continuous or available in real time, but the data will still enable valuable retrospective solar wind modeling studies.

TABLE E.B-13 Summary of SOLARIS's Potential Value to Space Weather Research and Operations

IDs	Mission Value for SWx	Mission Aspect of Interest	Impact on Research or Operations?	Priority
Mission as Proposed				
PR1	Improved solar wind modeling.	Magnetogram measurements over the poles for retrospective solar wind modeling studies.	Research	High
PR2	Improved CME propagation analysis, improved CME arrival times.	Coronagraph observations over the poles for retrospective CME analysis with potential for improved CME arrival times.	Research	High
PR3	Improved solar wind modeling.	In situ solar wind plasma and magnetic field measurements from additional vantage points, including off Sun–Earth line and out of the ecliptic, for model validation.	Research	High
PR4	Improved understanding of solar dynamo and solar activity.	Magnetogram measurements over the poles for improved understanding of the solar dynamo with potential to improve longer-term climatological forecasts of solar activity.	Research	Medium
Mission Augmentations				
AR1	Improved understanding of SEP acceleration and transport.	The addition of an energetic particle instrument would improve understanding and predictability of SEP intensity and extent throughout the heliosphere.	Research	High
AR2	Improved understanding of active region evolution and solar flares.	The addition of an X-ray instrument, in particular X-ray imaging extending to hard X-ray energies, would improve understanding of active region evolution and flaring activity.	Research	Low
AR3	Increased understanding of the global coronal magnetic field, greater solar coverage.	The addition of a second identical spacecraft phased by 120 to 180 degrees would increase coverage of the Sun and scientific understanding of global processes.	Research	Low
AO1	Real-time downlink for forecast operations.	Real-time coronagraph, magnetogram and EUV image data would benefit space weather operations, with real-time tracking of active regions not viewable from the Sun–Earth line and tracking of CMEs off the Sun–Earth line and of the ecliptic.	Operations	High

NOTES: IDs are identification codes used and assigned below; PR: As proposed value to SWx research; PO: As proposed value to SWx operations; AR/AO: same with mission augmentations. Acronyms are defined in Appendix H.

This is rated as high value to space weather research because of the potential for polar magnetic field information to significantly improve, for example, solar wind models in the near future.

- **PR02:** ***(High)*** **Top-down coronagraph observations made over the poles** offer a new vantage point from which to study CME propagation. This can provide information about CME longitudinal deflection, the longitudinal extent of the CME-driven shock, both of which will help to determine CME properties along different directions in the ecliptic plane. Likewise, these measurements will not be continuous or available in real time, but the data will still be valuable for retrospective studies, which are required to improve our understanding of CME and shock propagation in the heliosphere. Long term, such improvements are required for more accurate, CME arrival time forecasts with improved lead time (e.g., geomagnetic storm forecasting) and understanding and predicting SEP impacts at Earth (e.g., aviation industry), Geospace (satellite industries), cislunar and Mars environments (e.g., astronaut health and single event upset, SEU, to vital exploration life sustaining equipment) from CME driven shocks. The studies would serve as a proof of concept for the value of off Sun–Earth line observations made out of the ecliptic. *This is rated high value owing to the importance of understanding CME evolution and progression for space weather research and impacts.*
- **PR03:** ***(High)*** **In situ solar wind plasma and magnetic field measurements** will provide additional measurements with which to validate solar wind models, including in the vastly undersampled regions at high solar latitudes. As part of the suite of in situ instrument packages, they will be powered on and collecting data during both encounter and cruise phases. In particular, leaving the Sun–Earth line and going out of the ecliptic will really test our ability to model the solar wind throughout the heliosphere, instead of optimizing our models to fit the observations at one or two points. *Additional solar wind observations from a different vantage point in the heliosphere is rated as high value owing to the potential for better understanding of the 3D structure of the solar wind.*
- **PR04:** ***(Medium)*** **Improved understanding and predictability of the solar dynamo and solar cycle activity** might enable longer-term climatological forecasts of solar activity and future solar cycles.
    - Solar cycle predictions are used by NASA, for example, for a number of planning activities including estimated dose for astronauts (different mission profiles that range from a few days in orbit to multimonth stays on the ISS to long-duration exploration missions). Accurate solar cycle prediction is especially important input for long-term space exploration planning and for monitoring and balancing astronaut career dose limits versus availability for future missions. (See the 2022 report *Safe Human Expeditions Beyond Low Earth Orbit*; NASA Engineering and Safety Center 2022.) Timing and size of the solar maximum are important factors. The medium-priority characterization reflects the balance with other nonsolar cycle related mission planning constraints (budget, hardware, etc.), which can readily influence mission timing. Forecasting the day-to-day variability is significantly more important.
    - Solar cycle predictions are also used by the commercial sector and satellite industry to scale the mission requirements and spacecraft designs to meet the expected space environment conditions during the design lifetimes of future missions.
    - *This is rated as medium value to space weather research owing to the potential improvements in solar cycle predictions for customers who use this information for planning purposes.*

Value to Space Weather Operations

No real-time downlink is planned for the proposed mission in its *current* format. *As proposed*, the mission is therefore not capable of providing inputs to real-time operations.

Remote sensing:

- The benefit to operations as proposed is tangible. The mission would demonstrate the value of remote sensing polar observations for constraining global coronal magnetic fields and providing “top down” views of CMEs. This is a valuable step in the Research to Operations process and could provide a proof-of-concept for a future operational mission concept.

In situ observations:

- The planned orbit will result in the spacecraft spending large amounts of time away from the near Earth environment. Solar wind measurements over the polar regions, and when the spacecraft samples non-Sun-Earth longitudes out of the ecliptic, will potentially offer data assimilative proof-of-concept corrections to solar wind models that could enhance forecast accuracy in the future.

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

Value to Space Weather Research

- **AR1:** ***(High)*** **Energetic particle instrument.** The addition of an energetic particle instrument would increase the value of this mission as this could improve our understanding of SEP extent/connectivity when the spacecraft is significantly off the Sun–Earth line. Adding an instrument off the Sun–Earth line and out of the ecliptic would improve our understanding of SEP acceleration and transport in the heliosphere and assess the capability of models to accurately represent system wide SEP fluxes. Furthermore, GCR is an important input to all space radiation analysis (Single Event Effects on satellites, radiation shielding studies, astronaut health).
    - A pair of SEP instruments, such as SIS + HET from Solar Orbiter, to measure H-Fe from 1 to >400 MeV/nuc, can be implemented to satisfy the requirements that GOES-R uses for their SGPS and EHIS instruments (protons and heavy ions up to Ni from 1–>500 MeV/nucleon). Further increasing heavy ion measurements to 1 GeV/nuc would allow characterization of the GCR.
    - *Understanding the spatial extent and characteristics of energetic particles throughout the heliosphere is an important space weather research topic. Particularly with the planned human exploration missions beyond low Earth orbit, our understanding in this area must improve to ensure astronaut safety. The addition of an energetic particle instrument is rated as high value for space weather research.*
- **AR2:** ***(Low)*** **Soft X-ray intensity measurements.**
    - 0.1–0.8 nm and 0.05–0.4 nm passbands (i.e., see GOES observations) enable identification of solar flare events and classification using NOAA/SWPC's flare class scale.
    - The X-ray instrument in the GOES/EXIS suite could be used for a cost estimate.
    - X-ray observations over the solar poles and off the Sun–Earth line would enable better understanding of active region and flare site evolution and development over the full Sun.
    - For additional cutting-edge research purposes, X-ray imaging and/or extension of passbands into the hard X-ray spectrum and finer sensitivity (than say RHESSI) would partially fill observational gaps in historic measurements that might enable advances in predictive capability.
    - *The addition of soft X-ray measurements would provide useful contextual information and inputs for space weather models. This is rated as a lower priority than the addition of an energetic particle instrument.*
- **AR3:** ***(Low)*** **Addition of a second, identical spacecraft.**
    - With the addition of a second, identical spacecraft phased by 120 to 180 degrees in the same orbital plane, co-temporal observations of both poles could be achieved, significantly increasing the science return on global coronal magnetic field structure and high-speed solar wind characteristics relevant to space weather forecasting research.
    - Significant solar coverage could be achieved in combination with Earth or L1, L5, L4, and STEREO-A (when it is on the far side of the Sun from Earth). See advantages of full-Sun coverage in the NASA Space Weather Gap Analysis report and the Firefly mission concept. Note, however, that co-temporal observations from Earth/L1, L5, L4 and STEREO-A are not part of this mission concept, nor are they currently in place (L4, L5) or guaranteed to be operational (STEREO-A) for the timeframe of the SOLARIS mission. This would be a risk to significant solar coverage being achieved by the augmentation suggested here.

- *The addition of a second, identical spacecraft could take us one step closer to full-Sun coverage; however, co-temporal observations from other platforms are still needed to achieve this and it is not the primary objective of this mission. Therefore, this is currently rated as low impact to space weather research.*

Value to Space Weather Operations

- **AO1: *(High)* Addition of real-time downlink.**
  - **Real-time coronagraph data.**
    - *Cruise phase:* The addition of a real-time downlink for coronagraph data, during the spacecraft *cruise* phase, would be beneficial for space weather operations. This would allow for real-time CME tracking, off the Sun–Earth line and out of the ecliptic, for input into models and will likely improve CME arrival time forecasts (there may also be secondary benefits for SEP models which utilize CME characterizations as inputs). However, the changing distance from the Sun will likely introduce challenges for a coronagraph that would need to be solved for observations during cruise phase to be beneficial.
    - *Polar pass:* The addition of a real-time downlink during the polar passes may not be feasible, owing to a limitation in telemetering data during helioseismic data collection, owing to the potential for artifacts in the data. However, if it were possible to telemeter during this phase, the data would be extremely beneficial for space weather operations, providing a, not seen before, "top-down" view of CMEs heading toward Earth, Mars, and other locations of interest.
    - *Real-time coronagraph data from SOLARIS is rated as high value for space weather operations owing to the immediate improvement that observations from different vantage points could make to forecast operations and, for example, the arrival time of CME forecasts.*
  - **Real-time magnetogram data.**
    - *Cruise phase:* Real-time magnetogram data collected during the cruise phase could be useful for tracking active regions that are near the limb or not viewable from a Sun–Earth line vantage point. Data could be used as an input to synoptic magnetic field maps that are used as an input to solar wind models. Data from the far side would lessen the need for flux transport models such as ADAPT to simulate the emergence and evolution of active regions not visible from Earth. However, much of the SOLARIS cruise phase will be distances beyond 1 AU, consideration of the magnetogram spatial resolution would need to be considered. Furthermore, intercalibration with any other (L1, L5, or ground-based) magnetograms would be required, which is a nontrivial problem.
    - *Polar pass:* As noted for the coronagraph, real-time downlink for the magnetogram, during the polar passes may not be feasible owing to ongoing helioseismic observations. However, if it were possible, magnetogram data could be returned for *situational awareness* (only) of active regions not visible from the Sun–Earth line. Furthermore, the use of polar magnetic field data in solar wind models would need to go through a period of research and validation before being suitable for transition into space weather operations.
    - *Real-time magnetogram data is rated as medium value for space weather operations. The advantages of having additional magnetogram data off the Sun–Earth line and out of the ecliptic could show promise for improving models and forecasts but would need to go through a period of intercalibration, development, demonstration and validation, meaning improvements would not be immediate.*
  - **Real-time EUV data.**
    - Real-time EUV during the cruise and polar phases would allow for continuous observations of solar activity from the SOLARIS mission. The spacecraft's orbit off the Sun–Earth line and out of the ecliptic would add an additional vantage point to the operational observing system.
    - *Real-time EUV data is rated as medium value to space weather operations owing to the additional situational awareness of solar activity from vantage points off the Sun–Earth line and out of the ecliptic. Use in operations could be achieved in the near future.*
    - For a real-time downlink and telemetry augmentation to the SOLARIS mission, dedicated DSN service—*or some equivalent for dedicated space weather telemetry streams from observatories in*

deep space—would need to be made available. Considering the high-demand and limited resources of the DSN, it may be problematic to rely on those ground stations. Furthermore, any SOLARIS data that would be made available for use in near-real-time analysis and/or modeling would need to properly account for speed-of-light time delay from SOLARIS in its distant, heliocentric orbit with respect to Earth.

E.B.11 Space Weather Contributions from the Concept SOURCE Mission

Mission Concept Summary

The Synchronized Observations of Upflow, Redistribution, Circulation, and Energization (SOURCE) mission is a constellation of five in situ and imaging observatories designed to investigate the full life cycle of core plasma, from its ionospheric origin to its magnetospheric energization and impact. SOURCE is proposed as a "Discovery-class" (i.e., ~$700 million to $800 million) PI-led mission with SOURCE imaging quantifying the distribution, composition, system-level transport, and dynamics of core plasma, while SOURCE in situ measurements capture the local transport and physical processes that are responsible for creating highly structured core plasma distributions of the plasmasphere, dense O^+ torus, and warm cloak. The SOURCE mission duration will be 4 years for development, plus 2 years of science operations.

The SOURCE constellation includes

- Two spinners (i.e., M1 and M2) in LEO (350 km × 1,500 km) with four instruments, each making in situ measurements, as follows:
  - Core Plasma Analyzer: Distributions of atomic and molecular ions, and pitch angle distributions of core electrons, the cold plasma that safely discharges surface charging.
  - Dual Electron Spectrometer: spectra/pitch angle distributions of hot electrons which cause spacecraft surface charging.
  - Hot Plasma Composition Analyzer: Spectra/pitch angle distributions of hot ions.
  - Fields Suite: Background B-field vector, 3-axis magnetic plasma wave components, electron plasma density and upper hybrid resonance, quasi-static low-frequency waves, and DC electric field.
- A nadir-pointed imager spacecraft (i.e., M3) in HEO (20 R_E circular polar, 5d period) containing the following:
  - Two EUV instruments providing global images of plasmaspheric He^+ (EUV-A) and O^+ (EUV-B).
  - GPS Receiver: Total electron content (TEC) between SOURCE spacecraft and existing GNSS assets.
  - Geocoronal Imager: Neutral H exosphere.
  - Energetic Neutral Atom Suite: Two imagers measuring low and medium ENAs.
- An in situ spinner (i.e., M4) in GTO (geosynchronous transfer orbit, 1.1 R_E × 5.8 R_E low-inclination) with the following instruments:
  - Helium Oxygen Proton Experiment: Spectra and pitch angle distributions of atomic ions.
  - Sensor-Panel-Bias System: Spectra/pitch angle distributions of hot electrons.
  - Fields Suite: Background B-field vector, 3-axis magnetic plasma wave components, electron plasma density, and quasi-static low-frequency waves, and DC electric field.
- An in situ spinner (i.e., M5) in Highly Elliptical Geocentric (HEG, 4 R_E × 15 R_E inclined) orbit with the following instruments:
  - Thermal Ion Dynamics Experiment: 3D distributions of atomic and molecular ions.
  - Active Spacecraft Potential Control.
  - Dual Electron Spectrometer: Spectra/pitch angle distributions of hot electrons which cause surface charging.
  - Hot Plasma Composition Analyzer: Spectra/pitch angle distributions of hot ions.
  - Fields Suite: Background B-field vector, 3-axis magnetic plasma wave components, electron plasma density which prevents surface charging, and quasi-static low-frequency waves, and DC electric field.

M1/M2 give detailed information on ionospheric outflow in the polar wind and plasmasphere refilling, polar cusp and nightside auroral zone. The instrument suites and mirror orbits provide the first comprehensive observational effort to disentangle the processes causing ion outflow.

M3 and M4 measure, both directly and with imaging, the resultant filling and transport of the plasmasphere, plasma trough and O^+ torus in the inner magnetosphere. The cross-scale observations will advance understanding of how the plasmasphere is formed and by what mechanisms ions are trapped within it, by what pathways the dense O^+ torus is created, and how the plasmasphere is eroded and redistributed.

The M5 spacecraft, co-planar with M1 and M2, will allow for observations of the transport of ions through the lobes and into the midplane. Ion composition instruments plus spacecraft potential control will capture the transport of the coldest ions. M5 will also observe the life cycle of outflowing lobe cold ions as they are transformed into the energies of the plasma sheet, cloak and ring current based on where they enter the neutral sheet region. This knowledge will advance understanding of how the ionosphere mass-loads the magnetotail and gets energized, and has major potential implications for reconnection onset, "sawtooth"-event generation, bursty bulk flows and other magnetospheric dynamics.

Two SOURCE launch scenarios on either a Falcon 9 or a Vulcan rocket are under consideration, both requiring onboard spacecraft propulsion to achieve final science orbits after insertion.

A. A single SOURCE launch to high inclination with 2 restarts (ReSt) of upper stage motor:
   1. Insert M1, M2 to LEO.
   2. ReSt and insert M3, M5 to HEO.
   3. ReSt, insert M4 cislunar, use lunar swingby to lower M4 inclination to near-equatorial.

B. Two launches:
   1. M1, M2 to LEO high inclination.
   2. M3, M4, M5 to $20R_E$ GTO-like or cislunar, with a lunar swingby to raise M3 and M5 inclination to >70 degrees.

Space Weather Value of the Mission as Proposed (Table E.B-14)

Value to Space Weather Research

As many of the sensors envisioned for SOURCE have past analogs, SOURCE provides new opportunities through simultaneous complementary measurement of relevant parameters, compared to past missions which had a sparser system of observations.

- **PR1:** ***(High)*** **In situ plasma.** Hot electron plasma (~10 keV) causes surface charging and its altitude structure is not well known. Improved surface charging plasma climatology models contribute to more efficient, robust spacecraft designs. Pertains to SOURCE observatories M1, M2, M4, and M5.
- **PR2:** ***(High)*** **Cold plasma (plasmasphere)** can protect slow-moving (high-altitude) vehicles from surface charging by equilibrating charge on all surfaces. Present plasmasphere models are not trusted well enough to be used in operational surface charging applications, but more data, especially global data from the EUV imager, could change that through improved empirical and simulation models. Pertains to SOURCE observatory M3.
- **PR3:** ***(Medium)*** **Vector magnetic field data** fills in some important spatial gaps. These data could readily be incorporated into empirical magnetic field models that are sometimes used operationally. The data could also be used for data assimilation and (in LEO) to constrain locations of FACs and electrojets (AMPERE). Pertains to SOURCE observatories M1 and M2.
- **PR4:** ***(Medium)*** **Vector electric field** measurements are used to constrain the polar cap potential and auroral convection, and can be used to improve empirical models which are then used by numerical simulations to improve representation of global magnetic and plasma configuration. Pertains to SOURCE observatories M1, M2, M4, and M5.

TABLE E.B-14 Summary of SOURCE's Potential Value to Space Weather Research and Operations

IDs	Mission Value for SWx	Mission Aspect of Interest	Impact on Research or Operations?	Priority
Mission as Proposed				
PR1–2, PO1	Satellite charging environment.	Observations required to improve models of satellite charging environments throughout geospace. Even latent plasmasphere imaging can support ops.	Research and Operations	Research: High Operations: Medium
PR3, PR4, PO1	Auroral impacts: Ground-induced currents, clutter, scintillation. Magnetospheric state.	Observations of low-altitude electromagnetic fields constrain auroral dynamics. Magnetospheric fields affect mapping, connectivity, transport.	Research	Medium
PR5	Satellite drag environment.	Study thermospheric density proxy from geocoronal imaging data.	Research and Operations	Low
Mission Augmentations				
IDs	Mission Value for SWx	Suggested Augmentation	Impact on Research or Operations?	Priority
AR4, AO1	Space radiation in multiple unusual orbits for radiation environment characterization.	Proton radiation sensors, real-time telemetry.	Research and Operations	LEO/real time: High M3: Low
AR2–3, AO1	Near-real-time auroral activity in full ovals in both hemispheres.	FUV/X-ray imagers, real-time data stream.	Research and Operations	FUV: Medium X-ray: Low Real time: High
AR1, AR6, AR7, AO1	Space situational awareness of satellite charging environments throughout LEO, MEO GEO, and HEO.	Near-real-time cold plasma (remote via GNSS), hot electrons (in situ), and internal charging (in situ) sensors.	Research and Operations	Research: Medium Real time: High
AR1, AO1	Satellite drag environment.	Precision orbit determination (via GNSS sensor) for thermospheric density estimates.	Research and Operations	Research: Medium Real time: High
AR5	Relating observed satellite charging environment to actual charging/discharge events.	Add spacecraft charging sensors (e.g., charge-discharge monitors) on all spacecraft but M3.	Research	High

NOTES: IDs are identification codes used and assigned below; PR: As proposed value to SWx research; PO: As proposed value to SWx operations; AR/AO: same with mission augmentations. Acronyms are defined in Appendix H.

- **PR5:** ***(Low)*** **Thermospheric density.** Geocoronal imaging, while not a conventional source of data on the thermosphere, might yet provide data, especially on extreme thermospheric enhancements. Pertains to SOURCE observatory M3.

Value to Space Weather Operations

No real-time downlink is planned for the proposed mission in its *current* format. As proposed, the mission is therefore not capable of providing inputs to real-time operations, but as noted below SOURCE data can still be used for satellite operations, *in those cases where data are still valuable up to 1–2 days after the fact*.

- **PO1:** ***(Medium)*** **Satellite anomaly resolution.** For many satellite operators, anomaly resolution or forensics is the higher priority over forecast and nowcast. While anomaly triage can begin almost immediately after an event is detected, data coming in up to *~2 days* after an anomaly can contribute to a decision to return a vehicle to operations. SOURCE measurements that can contribute to this include suprathermal electron distributions and current systems at low altitudes, plasma density at medium and high altitudes, and auroral imagery. This pertains to all five SOURCE observatories. (*Medium* owing to lack of real-time link.)

Suggested Augmentation to the Mission to Enhance Its Space Weather Value

Value to Space Weather Research

Several possibilities exist for extending past data sets. These additional sensors could enable us to learn how to process and exploit their data in real time, and they could be used in scientific studies and AI/ML models benefiting from the more extensive context data provided by SOURCE itself and by the modern heliophysics observation system.

- **AR1: *(Medium)* Fly (new) high-precision GNSS receiver on all vehicles.**
  - Proposed to be carried only on M3.
  - Adds factorial more point-to-point opportunities and geometries.
  - Requires achieving <~1 TECU (challenging new accuracy leads to *Medium* rating).
  - On M1 and M2, precision GNSS orbit data can be used to infer thermospheric density.
- **AR2: *(Medium)* Add FUV imager to M3.**
  - Large-area simultaneous auroral monitoring from high altitude, including satellite surface charging.
  - Value will be limited when vehicle observing geometry is compromised by solar albedo (significant technology challenge to make "solar blind").
  - Higher altitude complicates achieving valuable resolution.
  - Prior analogs: Image FUV and Polar UVI (note M3 is quite a bit farther away).
- **AR3: *(Low)* Add X-ray imager to M3.**
  - X-rays are slightly more relevant for surface charging than UV.
  - Higher altitude complicates achieving valuable resolution.
  - Prior analog: Polar PIXIE (note M3 is quite a bit farther away).
- **AR4: *(Low) and (High)* Add ~1–100 MeV proton sensors to M1/M2 (LEO) and M3.**
  - M1/M2: As noted earlier, LEO rated High because low-altitude gradients and their solar cycle variation are one of the largest uncertainties in satellite design (climatology) models.
  - M3 provides SEP observations outside of the magnetopause and at high magnetospheric altitudes, backs up GOES, and aids intercalibration. (Low because to first order gives same answers as GOES and other high-altitude platforms).
  - Prior analog: SAMPEX PET (low altitude <600 km), RBSP/ECT (high altitude).
- **AR5: *(High)* Add charge/discharge sensors to M1, M2, M4, and M5.**
  - SOURCE orbits (both in situ and remote sensing observatories) transit multiple regions of concern for spacecraft charging hazards. Considering this, spacecraft charging data—such as charge/discharge sensors, and/or spacecraft potential monitoring—would prove valuable for space weather research. There is no flight history of surface charging/discharge sensor in LEO, and a spinner is especially helpful to learn about attitude/illumination effects on surface charging phenomena. A charge/discharge sensor on the high-altitude vehicle with active spacecraft potential control would provide valuable data about how ASPOCs interact with the differential charging environment (ASPOCs control the vehicle potential relative to the ambient plasma, differential charging refers to different surface charged relative to each other).
  - Prior analog: SCATHA (high-altitude spinner), CRRES (GTO spinner).
- **AR6: *(Medium)* Add Electrons to HOPE on M4, M5.**
  - Nominal energy rage 1 keV to 30 keV.

- Cover same electron energy range as prior analog RBSP/HOPE.
- RBSP/HOPE covered electrons relevant to surface charging.
- Caveat: One or two points in the whole inner magnetosphere is not a priority for real time, so this is not listed under operations. Conversely, adding in situ plasma with charging/discharge sensors could raise this *High* owing to the ability to correlate.

- **AR7:** ***(Medium)*** **Add 40 keV to 5 MeV electron sensors to all observatories.**
  - Nominal energy range 40 keV to 3 MeV.
  - Since RBSP, we have learned that we can map radiation measurements from LEO to high altitudes and specify high-altitude electron hazards (SHELLS, PreMeVE). These models were trained on POES/MetOp SEM-2 and RBSP data. However, the era of the SEM-2 workhorse is coming to an end, and will be replaced with some combination of USSF/REACH and MetOp-SG/NGRM. This change in input observations will require retraining the empirical models. Adding these sensors in the SOURCE orbits will provide both the low- and high-altitude measurements and facilitate retraining the empirical models.
  - Furthermore, the eccentric LEO M1/M2 platforms provide a unique opportunity to map the altitude gradients and solar cycle variability in the LEO radiation environment, which has only been measured at fixed altitudes and/or with limited sensor capabilities. LEO altitude gradients are one of the largest uncertainties in the AE9/AP9-IRENE climatology models used for satellite designs. The spinners make this even more valuable, as they provide information about altitude gradients along the local field line.
  - Prior analog: RBSP.

Value to Space Weather Operations

- **AO1:** ***(High)*** **Addition of real-time downlink for space weather relevant data beacons.**
  - Near-real-time plasmasphere images every ~1 hour would be useful for mapping where the surface charging is not present and would apply to all high-altitude satellites. For polar vantage points, little modeling is required to interpret this. This type of All Clear indicator was highly valued by users according to the ABT report "Social and Economic Impacts of Space Weather in the United States." (Conversely, single-point or few-point in situ surface charging measurements—hot electrons—are typically only useful to the host vehicle or others flying very nearby, maybe ~0.1 R_E, so that is not a real-time priority.)
  - Near-real-time space-to-space TEC would also be useful if downlinked within ~1 hour, and TEC resolution is better than ~1 TEC unit. Requires real-time ingestion into an assimilative plasmasphere model.
  - Near-real-time magnetometer and electron velocity distributions from M1, and M2 could help identify FACs and electrojets. Real-time magnetometer data from M3, M4, and M5 provide some value in constraining global magnetic field models, which can be used for mapping hazards around the magnetosphere and constraining data assimilative space weather models.
  - Near-real-time FUV or X-ray imagery would allow development/demonstration of real-time auroral products (including electron surface charging).
  - Details on ionospheric density distributions and mass content in real-time were identified as gaps in the NASA Gap Analysis report; several of the SOURCE observations could be used to partially fill these gaps if data were available in real time.
  - Precision GNSS orbit determination in LEO can contribute to satellite drag estimation and situational awareness.
  - M1/M2 near-real-time proton radiation gradients provide data valuable to knowing the radiation altitude gradients in South Atlantic Anomaly. This is a specific issue for low-altitude operations, but does not typically require minutes' latency, but hours-day. These data can also supplement geomagnetic cutoff (solar particle access) assessments, which applies to LEO, MEO, and launch.

ANNEX E.C

THE CRUCIAL ROLE OF GROUND-BASED OBSERVATIONS IN ADVANCING SPACE WEATHER SCIENCE AND APPLICATIONS

E.C.1 Introduction

Understanding and predicting space weather phenomena are of paramount importance for safeguarding technological infrastructure and ensuring the safety of both space-based assets and humans involved in space activities. While space-based observations have significantly contributed to knowledge of space weather, ground-based measurements hold equal significance. In this section, the panel highlights the indispensable role of ground-based observations, specifically focusing on solar observations from the Global Oscillation Network Group (GONG), particle measurements via neutron monitors, and ground-based magnetometer measurements that have particular importance for space weather forecasts and applications. Other ground-based instruments, such as incoherent scatter (IS) radars, ionosondes, and riometers, are also important to fundamental space weather research, but not yet directly in applications. Therefore, they are considered out of scope and are not included in this section.

The panel's suggestions for the continuity and enhancement of ground-based space weather capabilities are detailed below. Particularly needed is increased support from the National Oceanic and Atmospheric Administration (NOAA) to further advance operational ground-based observations.

E.C.2 Overview of Current Assets

Table E.C-1 provides a summary of the ground-based systems that are operated by U.S. agencies in support of space weather research, applications, and operations. The list of assets is not presented in any particular order and additional details about some of the assets are presented below the table.

Solar Observations from GONG

The Global Oscillation Network Group (GONG) is a vital ground-based observatory network that provides valuable data on the Sun's internal structure, dynamics, and magnetic field. By capturing high-resolution images and precise Doppler velocity and magnetic field measurements, GONG enables scientists to study solar phenomena such as acoustic oscillations, sunspots, and solar flares. GONG also provides the only high-duty cycle H-alpha images of the chromosphere used by space weather forecasters to assess filament eruption CME events that often do not have accompanying X-ray flares but that can cause minor to moderate geomagnetic storms if they collide with Earth. GONG data contribute significantly to our understanding of solar activity and its impacts on space weather events, providing critical information for forecasting and mitigation strategies. GONG also provides the primary global solar magnetic field inputs to operational solar wind models such as the WSA-Enlil model. Continued support for GONG and, as discussed in the NOAA Science Advisory Board report (NOAA SAB 2023), a firm commitment to develop the "next generation" follow-on, ngGONG, will ensure a comprehensive understanding of solar processes and improve space weather predictions.

Particle Measurements via Neutron Monitors

Neutron monitors are essential tools for studying high-energy particles, particularly galactic cosmic rays (GCRs) that originate from supernovae and other astrophysical phenomena, as well as solar energetic particles that are accelerated during solar flares and coronal mass ejection (CME) shocks. These ground-based detectors continuously monitor the secondary particle flux from GCRs and the highest energy component of solar energetic particle events as they interact with Earth's atmosphere. This continuous monitoring is crucial for studying the effects of solar events on space weather.

By tracking variations in GCR flux, neutron monitors provide early warning indicators for potentially hazardous energetic particle events, solar eruptions, and space weather storms. They also provide crucial observational

TABLE E.C-1 Ground-Based Observing Evaluation

Ground-Based Asset or Network	Role in Advancing SWx Science	Role in SWx Operations	Current Status/ Threat Level	Value to Operations	Value to Research	Goal Connection
GONG solar observing network	Many science models rely on GONG synoptic global magnetic field maps as input. Need ngGONG to continue synoptic magnetogram maps as well as helioseismology detection of far side active regions and near-side emergence events as part of ongoing research. GONG synoptic magnetic field maps are also used by the CLEAR SWx center for SEP prediction research.	GONG network provides synoptic global magnetic field maps used as an input to the WSA-ENLIL+Cone model running operationally at NOAA SWPC and USAF 557th Weather Wing to support geomagnetic storm forecasts and watches/warnings/alerts.	ngGONG not yet funded for development. Threat of interruption of solar magnetograms used in operational solar wind models if not started by ~2025.	Critical	Important	1—Eruptions 5—Bz
Mauna Loa Solar Observatory	Provides coronograph observations of the low corona (1.03–1.5 $R_{\odot}$) with Stokes polarimeter information that can provide plan of sky magnetic field information.	Information from K-cor is provided to SWPC, SRAG, and M2M office on trial basis because CMEs can be seen in the low corona before space-based observations.	Funded as part of the ongoing award to HAO as part of NCAR. COSMO is being developed as midscale project to create a 1.5 m corongraph and other instruments to expand on the capabilities of MLSO.	NA	Critical	1—Eruptions 5—Bz
Daniel K. Inouye Solar Telescope	4m mirror allows for highest resolution images of Sun and polarimetric IR measurements in the corona. Instruments include Visible Spectropolarimeter for magnetic field information, Visible Broadband imager for high resolution of solar surface and atmosphere, Visible Tunable Filter for 2D surface magnetic field, diffraction limited near infrared spectro-polarimeter for 2D spectral and spatial information, and cyrogenic near infrared spectropolarimter for coronal magnetic fields.	None	Recently made operational and plans for a 44-year life cycle. However, the NSF has not committed to fund full Inouye operations beyond 2024.	NA	Very Important	1—Eruptions 5—Bz
Expanded Owens Valley Solar Array (EOVSA) and Owens Valley Radio Observatory (OVRO-LWA)	EOVSA is a solar dedicated instrument with 13 antennas observing between 1–18 Ghz. It observes the sun daily. EOVSA provides close-up information about the initiation and low-coronal development of eruptive events. There is an associated flare catalogue of the observations and an automated flare imaging pipeline is currently under development. OVRO-LWA is a 352-antenna all sky array observing between 25–88 MHz. It is currently undergoing an upgrade to allow us observations of the sun at all times during the day. OVRO-LWA provides the “middle corona” manifestations like type II bursts (shocks) and the radio counterpart of CMEs.	Not a known operational input currently.	Currently funded by NSF Solar with an expansion midscale project called FASR under development.	N/A	Very Important	1—Eruptions 5—Bz

continued

TABLE E.C-1 Continued

Ground-Based Asset or Network	Role in Advancing SWx Science	Role in SWx Operations	Current Status/ Threat Level	Value to Operations	Value to Research	Goal Connection
	The spectral information from both radio arrays provides physical parameters including magnetic field.					
ALMA solar observations		Not a known operational input currently.		N/A	Very Important	1—Eruptions 5—Bz
Solar radio burst network (RSTN)	Can be used to study CME acceleration physics and coronal radio generation via thermal and nonthermal mechanisms.	Provides solar radio burst nowcasting capability to the NOAA SWPC and USAF 557th WW forecast offices in real time. Data used as an input to SWPC's current operational proton prediction model. Used by SRAG for human space exploration decision support. Type II radio burst info used as a first guess for CME speed by SWPC forecasters.	DoD/USAF currently operates the RSTN system but has not upgraded the antennas or software in many years. There is a critical threat to the system owing to retirement of key personnel with unique knowledge. The process for upgrading to a software radio system has been stalled and is in danger of being terminated.	Critical	Important	1—Eruptions 5—Bz
F10.7 cm solar radio measurement	F10.7cm radio observations are the second longest continuous record of solar activity after sunspot counts. Although a "proxy" for solar ultraviolet irradiance that will likely be replaced in models by direct measurements, the solar cycle historical record is a very valuable source of solar cycle information.	Currently used as an input to the WAM-IPE and geospace models running operationally at NOAA SWPC. Used by SRAG for situational awareness and premission dose projections. Also used by USSF in LEO satellite conjunction risk assessment models.	The only remaining regular F10.7cm measurements is made by the Dominion Astrophysical Observatory in Penticton, Canada. Funding for this facility is uncertain and the community is in danger of losing this important historical data set.	Critical	Important	2—Thermosphere 10—Solar cycle
Interplanetary Scintillation Network	Observations of metric radio burst location will further our understanding of particle acceleration. Association of radio burst source locations may further our understanding of SEPs.	Currently not used in any operational settings because the accuracy and reliability of CME arrival time predictions using this method have not been verified.		Important	Critical	1—Eruptions 5—Bz
Simpson neutron monitor network	One of few observations of highest energy SEPs (indirect measurement). Detected events are among the most extreme and rare of SEP event and their generation is not well understood. They are hard to study because of their rarity. Most space-based SEP observations do not go above a few 100 MeV.	Characterization of SEP proton spectra used as an input to the operational CARI-7 aviation radiation model running at NOAA SWPC.	NSF/AGS committing resources and funding. The majority of the U.S. network provides data in RT to the Neutron Monitor Database.	Critical	Important	13—Aviation

			Work is under way to incorporate data from Mount Washington and Durham into NMDB. * Simpson Neutron Monitor Network is currently funded by 3- to 5-year PI-led science proposals with some stations with only 1 or 2 years of funding currently promised.			
USGS magnetometer network		SWPC uses USGS geomagnetic data for the operational geoelectric field nowcast products.	USGS operates 6 geomagnetic observatories in CONUS. Regional impacts require resolution of ~200 km. Some additional real-time monitors are operated using short-term research funding.	Critical	Very Important	6—GIC
(High-rate) GNSS scintillation measurements		SWPC actively working to use data from ground-based GNSS receivers to support operations.		Critical	Critical	11—Ionosphere
(Low-cost) GNSS receivers	Measurements of path integrated TEC that support tomographic inversion to 3D profiles, or assumed FoF2. Used for specification of ionospheric state and identification/tracking of specific disturbances (TIDs, Polar Cap Patches, etc.).	RT ROTI supports prediction/specification of PNT errors in short-term forecasts as well as ICAO space weather advisories. Supports RT ionospheric electron density assimilative models GloTEC model for nowcasting of ionospheric conditions as well as those—e.g., IDA4D—under development by AFRL and JHUAPL.	Multple national networks. Large compliment of U.S.-led measurements. Madrigal TEC maps are near-RT supported by NSF.	Critical	Critical	11—Ionosphere
HF Sounding (ionosondes, oblique sounders)	Direct measurements of HF ionospheric propagation conditions overhead. If scaled properly can determine FoF2 in near real time. Supports RT ionospheric state specification.	Not a known operational input currently, although SWPC actively working to use data from ionosonde data to support operations.		Very Important	Critical	11—Ionosphere

continued

TABLE E.C-1 Continued

Ground-Based Asset or Network	Role in Advancing SWx Science	Role in SWx Operations	Current Status/ Threat Level	Value to Operations	Value to Research	Goal Connection
Riometers	Capable of real-time polar-cap absorption alert/status, D-region HF absorption (D-RAP), and provides information about regions of ring current precipitation with potential coupling to SSA models such as SHIELDS. Emerging development to support these capabilities but requires R2O development.	Not known to be used in current operations. Previous work had utilized real-time data (30-MHz transionospheric HF absorption) for ingestion into an augmented DRAP for SEP impacts. ICAO space weather advisories address polar cap absorption, riometer observations could perhaps be used in future to support these advisories.	Multiple national networks in operations with aging hardware using analog technology from the 1970s. New systems being developed. International coordination via GloRiA. Natural Resources Canada (NRCan) investing in R2O for Canadian systems for UN-ICAO obligations.	Very Important	Critical	11—Ionosphere
Incoherent Scatter Radars		Not a known operational input currently.	NSF funded for science operations.	NA	Important	11—Ionosphere
SuperDARN	Capable of RT data from some radars and providing model augmented derived quantities such as polarcap size. Emerging development of SWx operations relevant products, requires R2O development.	Not a known operational input currently.	Support by NSF Space weather program on a 5-year grant cycle.	NA	Critical	12—Reanalysis
Optical Auroral Measurements (ASI, Spectrograph, etc.)	Existing capacity includes RT observations on the nightside (e.g., auroral and midlatitude airglow). Emerging science on connections to impacts as well as RT boundary detection (e.g., Ovation). Requires R2O development.	Not a known operational input currently.	Several large national networks. NSF funded in the United States (e.g., Mango, Alaska, THEMIS).	Important	Critical	7—Auroral Input
Neutral Wind Measurements (meteor radar)	Meteor radar data can be analyzed to provide accurate measurements of zonal and meridional neutral winds in the 80–100 km mesospheric altitude range. This is a difficult altitude range to access for measurements because it is above aircraft and balloon altitudes but below stable satellite orbit altitudes.	Meteor radar-derived mesospheric neutral winds are being assimilated into the NRL NAVGEM upper atmospheric model. NASA is funding the SWORD Center of Excellence to develop data assimilation, including meteor radar-derived neutral winds, into NCAR WACCM-X and NOAA WAM-IPE models.	Meteor radar data are generally accurate and the systems are relatively cheap to install and maintain compared to many other ground-based SWx observing systems. There is a worldwide network of near-real-time meteor radars being managed by NASA/GSFC. However many more stations are needed to fill global gaps in coverage that inhibit data assimilation usefulness in ITM models.	Very important	Important	2—Thermosphere

			The network also needs to be more reliably maintained and the data more reliably analyzed, transmitted, and centrally archived to be considered a truly operationally reliable system.			
Airborne atmospheric radiation measurements (LET spectra and TID)	Improved understanding of the steady state atmospheric ionizing radiation environment (SSAIRE).	Validation of operational aviation radiation models. Observations for data assimilative aviation radiation model.	Measurement campaigns are sporadic and there have not been enough measurements during large SEP events.	Very Important	Very Important	13—Aviation
Fabry-Pérot Interferometers	Ground-based FPIs provide a sensitive measurement of ionospheric plasma flows and mesospheric neutral winds through airglow imaging and doppler velocity analysis.	Not currently used in operations but could provide a reliable source of mesospheric neutral winds for assimilation into whole atmosphere models if a global network with real-time data handling were developed.	Limited number (<10) of FPI instruments distributed around the world. Funded primarily by NSF. No RT data flow for any systems yet. NASA ICON mission demonstrated value of FPI data from orbit but ICON failed on orbit in December 2022.	NA	Important	2—Thermosphere, 11-ionosphere

NOTE: Acronyms are defined in Appendix H.

inputs for aviation radiation models, such as the FAA's CARI-7 model, currently running at NOAA SWPC in support of radiation advisories for the International Civil Aviation Organization. Characterization of high-energy (≥500 MeV) SEP proton and alpha particle spectra, which are most impactful for the radiation environment at aviation flight levels, cannot be accurately determined from the GOES particle sensors alone.

The U.S.-owned and -operated Simpson Neutron Monitor Network consists of 10 neutron monitors primarily funded for scientific research. The network, distributed in the western and northern hemispheres, is currently maintained and operated by the Universities of New Hampshire, Delaware, and Wisconsin-River Falls with funding support from the National Science Foundation (NSF). Stations within the network do not currently have the computational reliability and equipment redundancy required to support forecast operations. Optimizing the U.S. neutron monitor network and supporting operational data collection capabilities will enable more accurate space weather forecasting and better protection for satellites, astronauts, and vital technological systems. International partnerships are required to leverage the global neutron monitor network to ensure regional information.

Ground-Based Magnetometer Measurements

Ground-based magnetometers are indispensable tools for monitoring variations in Earth's magnetic field caused by solar activity and space weather events. Magnetometer measurements provide essential data for detecting geomagnetic storms and assessing their potential impacts on power grids, communication systems, and GPS navigation. Ground-based magnetometers enable scientists to track the evolution of magnetic disturbances and provide real-time information for space weather models and forecasts. By supporting the expansion and modernization of ground-based magnetometer networks, NOAA can improve space weather prediction accuracy and enhance our ability to mitigate potential risks.

GNSS Measurements

The availability of ground-based GNSS measurements provides information about scintillation and total electron content; however, critical coverage gaps limit space weather research within the globally coupled ionosphere–thermosphere (IT) system. Enhancing the coverage of GNSS scintillation measurements will be key to understanding impacts and developing operational models to support user needs in different regions (e.g., polar environments, low latitudes). A leading element of the current coverage gap is the polar environment and oceans. A network of sea-based buoy systems with capacity to measure scintillation would afford new data and would significantly advance IT science and support future operational models. Similarly, expansion and augmentation of known key terrestrial coverage gaps (such as Africa and the polar regions) would provide critical data to space weather science and operations.

Ground-Based Solar Radio Measurements

There are two major solar radio measurements currently used in space weather operations. The Dominion Radio Astrophysical Observatory in Penticton, Canada, produces the daily "F10.7" radio proxy for solar extreme ultraviolet (EUV) irradiance. This daily index, along with various temporal averages, is one of the primary inputs to operational models of thermospheric density used in LEO satellite conjunction analysis (e.g., the USSF High-Accuracy Satellite Drag Model, HASDM, which is based on the JB08 empirical model of thermospheric density). The DRAO F10.7 product will be the *only remaining regular measurement of F10.7 in the world* following the imminent closure of the Japanese Nobeyama Radio Observatory. While research is ongoing to use directly measured solar EUV irradiance in operational thermosphere models (e.g., from GOES/EXIS), the need for F10.7 inputs to the models will persist for at least another decade until they are replaced by more accurate physics-based or machine learning–based models. In addition, the continuous historical record of F10.7 measurements spans back to 1947; extending this record as long as possible would be of great value to solar cycle research. The primary researcher responsible for the F10.7 measurements has recently retired, and it is unknown how long DRAO will support continued daily operations.

The other major solar radio measurement used in operational space weather forecasting and nowcasting is the Radio Solar Telescope Network (RSTN), part of the Solar Electro-Optical Network (SEON) run by the USAF at four sites around the world. The RSTN Solar Radio Spectrograph (SRS) measurements are used in characterizing CMEs early in their propagation phase, producing the first speed estimates via the correlation with Type II radio burst frequency drift rates. In addition, RSTN RIMS (Radio Interference Measurement Set) data produces nowcasting alerts of solar radio bursts in the HF radio, OTH radar, and GNSS L-band ranges. Both SRS and RIMS data are acquired continuously at 1-second cadence. Radio bursts are rare and only episodically associated with major flares, meaning that there are no models for predicting these events and near-real-time nowcasting is the only method of warning operators of ongoing interference from "solar radio flares." The USAF has recently terminated a modernization/upgrade program for RSTN and the fate of the 50-year-old network remains unknown at this time.

E.C.3 Suggestions and Key Takeaways

The panel suggests that NOAA provide direct support for operational ground-based measurements.

Given the critical importance of ground-based observations in advancing space weather research and prediction capabilities, the panel suggests that NOAA significantly increases its support for ground-based measurement initiatives. This includes allocating resources for the maintenance, enhancement, and modernization of observatory networks like GONG, as recommended to the NOAA Science Advisory Board; neutron monitors; GNSS observations; ground-based magnetometers; and solar radio flux monitoring. By investing in these instruments and their associated data collection systems, NOAA can strengthen the ability to understand, model, and forecast space weather events, ultimately bolstering preparedness and resilience.

The panel suggests that agencies support international cooperation.

Because the utility of ground-based measurements can be greatly enhanced with global coverage, agencies are urged to consider international partnerships where possible to provide a wide distribution of observations. Coordination through international organizations such as the World Meteorological Organization and the Observing Systems Capability Analysis and Review (OSCAR) database may be highly useful in achieving this recommendation.

Key Takeaways

Ground-based observations are indispensable in advancing our understanding of space weather and improving our ability to predict and mitigate its potential impacts. Through solar observations via GONG, particle measurements using neutron monitors, and ground-based magnetometer measurements, scientists gain valuable insights into the Sun's behavior and its effects on Earth's space environment. By directly supporting these ground-based measurement initiatives, NOAA can significantly advance solar and space physics research and facilitate the transition of these advancements into operational use, thereby ensuring the safety and resilience of our technological infrastructure in the face of space weather events.

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F

Report of the Panel on the State of the Profession: A Vision for a People-Centered Solar and Space Physics (Heliophysics) Community

F.1 INTRODUCTION

This report of the Panel on the State of the Profession presents a people-centric, evidence-based discussion on the current state of the solar and space physics–heliophysics profession and highlights the barriers and pathways to developing and ensuring a healthy, accessible, inclusive, diverse, creative, collaborative, innovative, agile, accountable, and sustainable solar and space physics community in the next decade. Though there have been significant positive changes within the community over the past decade, much remains to be done.

This panel report provides actionable suggestions to enable the improvement of the community's culture, team dynamics, and supporting mechanisms. The panel focused on efforts that are directly applicable to and actionable within the solar and space physics community. Many broader issues, though also applicable to solar and space physics, have been raised in other recent decadal surveys (such as the decadal surveys on planetary science and astrobiology [NASEM 2022c] and on astronomy and astrophysics [NASEM 2023b]) and therefore are not elaborated upon here. This panel carefully considered topics raised by the community and chose to adopt a succinct, objective, and evidence-based narrative to help move the community to action.

The panel understands that language is important, contains cultural meaning, and can evoke implicit bias and be noninclusive (Kramsch 2014). With this understanding, the panel adopted "community input papers" instead of "white papers" and uses this term to describe the written input from the community to inform the decadal survey process.

The panel thanks those who are reading this report and recognizes that each one comes to this discussion with different lived experiences, privileges, and understanding of the social science research that underpins many of the suggestions made here. Some topics discussed in this report might be uncomfortable for some members of the solar and space physics community, for various reasons. The panel values lived experiences and hopes that this report's narrative does not professionally or personally hurt people from marginalized communities who have already been affected by their negative experiences.

The panel also hopes that those not from marginalized communities or early in their understanding of issues around diversity, equity, inclusion, accessibility, and other aspects of inclusion and fairness (DEIA+) see themselves as allies, champions, and change agents willing to fully engage in the required personal learning and activities that can create a new, more equitable, inclusive, diverse, and innovative solar and space physics community. Everyone needs to come together to learn from each other; have grace, empathy, and understanding; and approach this work with a growth mindset. Addressing such issues in a transparent way is fundamental for the health, vitality, and sustainability of the science community. The fact that part of the promoted discussion still causes discomfort in 2024 highlights the importance of shedding light on such topics. Furthermore, there is personal growth in not shying away from having conversations and implementing actions that make some uncomfortable (Woolley et al. 2022). The panel notes that some concepts and ideas described in this report may put some within the community on the defensive if their individual responsibility is not clearly distinguished from systemic or institutional structures (DiAngelo 2011).

The intention of the discussions raised in this report is to promote the well-being of the solar and space physics community, which is predicated on the well-being of individuals. The COVID-19 pandemic amplified the disparate effects of existing bias in the science community (Myers et al. 2020) and exacerbated what was already a mental health crisis in the broader science, technology, engineering, and mathematics (STEM) workforce (Abbott 2021; Kaska 2022) and specifically in solar and space physics (Nikoukar et al. 2023). The panel acknowledges that discussions of mental health still carry stigma that are often driven by corrosive cultures (Hall 2023) and that some of the suggestions made in this report are not actionable in some states due to recent state laws that create barriers for DEIA+ (Marijolovic 2023). Nevertheless, the panel chose to address those issues and make suggestions in this report.

For those who are new to the effort of culture change and may not be familiar with many of the recent reports and literature relevant to this work, this report provides data (specific to the solar and space physics community when available), brief summaries of relevant social science research, and descriptions of barriers that underrepresented people in the solar and space physics community face disproportionately. For solar and space physicists to thrive, the entire community needs to participate and welcome allies willing to learn and contribute to fostering inclusive excellence (Williams et al. 2005).

This panel report presents 14 identified barriers for the advancement of a healthy and sustainable solar and space physics community in the next decade and 29 actionable suggestions, of which 13 are considered high impact, divided into the following three categories:

- Short term: 7 actions that can be taken immediately;
- Medium term: 21 actions expected to be in place before the next midterm assessment; and
- Long term: 1 action expected to be in place by the next decadal survey.

The 13 high-impact suggestions are discussed in Section F.10.

Section F.2 provides an overview of the approach and background from research pertinent to the state of the solar and space physics profession. It highlights the importance of a healthy culture for the advancement of the solar and space physics community. A call for accountability at different levels and among different components of the solar and space physics community (including funding agencies and principal investigator institutions) permeates this panel report and is considered crucial to the progress and advancement of the solar and space physics profession.

Section F.3 covers the state of the solar and space physics profession.

Section F.4 covers the overarching goals for the next decade and offers suggestions for reaching those goals.

Section F.5 presents a detailed discussion of DEIA+, including the barriers to achieving full inclusion and fairness, and suggests approaches for overcoming those barriers.

Section F.6 looks broadly at the culture of research, and Section F.7 discusses teamwork. In both sections, the panel identifies barriers to achieving the stated goals and suggests ways to overcome them.

Section F.8 covers sustainable growth for the solar and space physics workforce—also known as the heliophysics workforce. It looks in detail at attracting, retaining, and advancing workers in the field and offers suggestions for overcoming the identified barriers.

Section F.9 offers the panel's summary and details its suggestions for the solar and space physics community. It includes a summary of the information received from the community input papers and details the alignment of the panel's suggestions with recent reports of the National Academies of Sciences, Engineering, and Medicine.

F.2 OVERVIEW

Like the development of the coupled systems framework of the solar and space physics discipline (consisting of the connected Sun and heliosphere, and the magnetospheres, ionospheres, and neutral atmospheres of Earth and other planets [NRC 2013]), the solar and space physics community consists of the closely coupled systems of individuals, departments, and institutions that are driven by funders, professional societies, and societal needs.

The recognition that the discoveries, missions, facilities, training, and education within the solar and space physics community are made, designed, and accomplished by people is the reason this 2024–2033 solar and space physics decadal survey explicitly included this Panel on the State of the Profession. Understanding the human element is essential for creating and fostering a healthy community that can attract and retain talent, provide opportunities for individuals and institutions to thrive, answer fundamental scientific questions, and meet urgent societal needs. In the past few years, the focus on the health and vitality of individuals and institutions as key for the overall success of the discipline has been highlighted in several important National Academies reports, including ones focused on sexual harassment (NASEM 2018), the foundations for healthy and vital research community in the National Aeronautics and Space Administration (NASA) (NASEM 2022a), and the importance of anti-racism, diversity, equity, and inclusion (NASEM 2023). These themes are the backbone of the findings and recommendations from the midterm assessment (NASEM 2020a) of the 2013 solar and space physics decadal survey (NRC 2013; hereafter "the 2013 decadal survey"), and the planetary science and astrobiology (NASEM 2022c) and astronomy and astrophysics decadal survey (NASEM 2023b), and significantly inform this report.

This report uses a systems model to address the tasks outlined in the statement of task (see Appendix A) to explicitly center people within the institutions and culture that enable the solar and space physics research and education enterprise. This systems model also provides the opportunity to identify the mutually reinforcing feedback between the components and integrate efforts across them (Graves et al. 2022). The solar and space physics community is made up of subcommunities studying the Sun, heliosphere, magnetospheres, ionospheres, and thermospheres, and the interconnections between them and the connections to technology and society. Understanding this system of systems helps organize science efforts. Analogously, the people that make up the solar and space physics community also work and study in different institutions and organizations—universities, labs, federal agencies, and industry: see Figure F-1. Understanding the interconnections among these components enables us to better understand and assess the community. It is important to recognize that suggested changes to one system component create repercussions beyond that system and therefore understanding the coupling among the components is critical for advancing the health and vitality of the solar and space physics and space weather community and the science it produces.

Physical scientists have frequently ignored that professional assumptions, beliefs, and biases are formed by the professional community and that they have perpetuated disparities in opportunities and outcomes for individu-

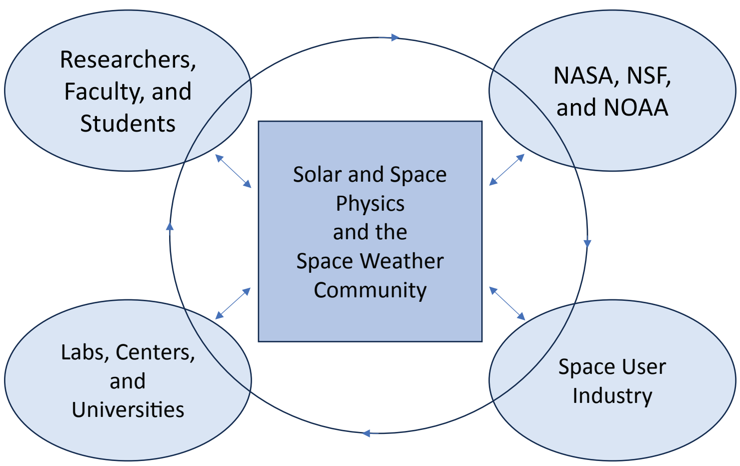

FIGURE F-1 Schematic of the solar and space physics system showing how its four components make up the solar and space physics and space weather community.
NOTES: Researchers, faculty, and students are explicitly included to highlight that the community is made up of individuals. NOAA, National Oceanic and Atmospheric Administration; NSF, National Science Foundation.

als and the discipline (Thorp 2023). Despite significant efforts to broaden participation in the STEM community in general, and in the Earth and space sciences community in particular, very little has changed in decades with respect to gender and racial diversity (Bernard and Cooperdock 2018). As shown in the next section, though, there are indications of small improvements in gender representation in solar and space physics since the 2013 decadal survey (NRC 2013), but continued lack of comprehensive data stymies assessment of progress and identification of issues. Like many systems, the solar and space physics research system's current culture is set by the dominant demographic group (White, male, able-bodied, heterosexual, cisgendered), which significantly influences the structures, values, and ideas of excellence and fairness (e.g., Culture—see definition in the Glossary of this appendix).

The solar and space physics community's current culture does not promote and is not conducive to fostering diverse, equitable, inclusive, health-centered, and accessible institutions, hindering its ability "to tackle strategic problems and maximize scientific return" (Diaz-Garcia et al. 2013; pp. 2008, 2017; NASA 2020b; Sommers 2006). This is reflected in the current demographic imbalance, and in findings from the limited climate surveys from individual institutions and community workshops. In part, this current culture is driven by the traditional metrics used for "success" in the discipline (awards, discoveries, missions, papers, citations, and graduates), which flow from the interactions of the components and depend on three pillars: (1) institutional policies and procedures; (2) behaviors and performance of individuals and leaders; and (3) the culture that attracts, trains, and supports people. Unfortunately, people-centered metrics—such as quality mentoring; supporting education and training; providing career development, effective team building, productive teamwork, health-promoting policies; and engaging in public communication—are often more difficult to quantify and therefore are not always assessed or rewarded as part of the traditional metrics of success. In addition, people from marginalized communities disproportionately support these activities (Simien and Wallace 2022; Zambrana et al. 2017) to the detriment of their career advancement (Gumpertz et al. 2017).

To better understand the influence of a dominant demographic group of any professional community in its definition of success (and in its overall culture), one needs to understand the metrics adopted by this community to evaluate or measure one's performance, how they are used, and how they perpetuate the status quo:

- The adopted set of metrics is used to evaluate excellence among the community workforce, defining the opportunities for an individual to be accepted, hired, promoted, and to receive awards (Araúla et al. 2016; Blair-Loy and Cech 2016).
- The adopted metrics are likely to reflect the dominant group's values, assumptions, experiences, biases, and stereotypes.
- Therefore, the definition of excellence of this community will often perpetuate the status quo, even when it is not intrinsically or overtly discriminatory, coercive, or prejudiced. This outcome also perpetuates the fallacy of meritocracy, in which success would be the result of individual talent, experiences, training, and motivation, and the inequalities would be the fault of individuals from marginalized populations and not the social system.

The impact of the current metrics of success was shown in the *Advancing Diversity* report (NASEM 2022): there are significantly fewer women or people of color acting as NASA mission principal investigators (PIs) compared to White men. *Advancing Diversity* raised other existing issues to justify this finding, such as the fact that mission PIs generally are at a senior level of their careers and since there are fewer senior women in the field, there would be a proportionally smaller number of female PIs. But one cannot ignore the role of bias in the traditional "success metric" adopted to evaluate those who aspire to be a mission PI. Hence, many of the suggestions made in *Advancing Diversity* focus on "fixing" access and training and not on the culture that perpetuates the inequalities. The concept of "inclusive excellence" (Williams et al. 2005) attempts to broaden the set of success metrics to include factors that are important to the health and vitality of the discipline and that are centered around DEIA+.

Much of the solar and space physics community does not actively participate in DEIA+ discussions and actions at the individual level because of society's and the discipline's belief systems and culture (Dancy and Hodari 2023). Furthermore, people in the dominant group generally lack awareness surrounding the climate of people of color and women or understand the impact of their implicit biases (NASEM 2023; Shelton 2013). A recent National

Academies (2023) report calls for systemic change at all levels (or components in the solar and space physics system shown in Figure F-1 above) and focuses on institutional-level “gatekeepers”—those in authority who can perpetuate inequality, exclusionary practices, and biases. This panel report makes actionable suggestions to funding agencies to support and hold accountable such gatekeepers at the individual, unit, and institutional levels to implement systemic changes to improve the culture of the solar and space physics community for all.

The role that harassment, discrimination, and bullying play in the professional culture also needs significant attention. The American Geophysical Union (AGU) helped lead the community’s redefinition of research ethics to include identifying as scientific misconduct—harassment, discrimination, and bullying in scientific endeavors (McPhaden et al. 2017). The National Academies itself revised its membership policies to expel members found responsible for research misconduct, including sexual harassment (Kaiser 2021). NASA and the National Science Foundation (NSF) are significantly behind the standard that the National Institutes of Health (NIH) has set to address these issues (NIH 2022). For example, NIH publishes annually the number of reported research misconduct cases and results from individual cases that include not only NIH employees, but also grantees. This panel report makes suggestions for improving the culture of research by minimizing scientific misconduct and providing policy and procedure suggestions to enable reporting and accountability.[1]

Centering community efforts around individual well-being also needs significant attention. Issues of financial stress, career instability, work–life imbalance, and mental and physical health, although they affect individuals across various demographics, disproportionately affect students, early career workers, and people from marginalized communities (Nicholls et al. 2022). These individual issues significantly hinder the health and vitality of the entire solar and space physics profession. This panel report calls for centering a health-promoting culture throughout the community.

F.3 STATE OF THE SOLAR AND SPACE PHYSICS PROFESSION: CURRENT STATUS

Studies of different subsets of the community, following from the 2013 decadal survey, are provided here to show the type of data that are important to be routinely collected. Bagenal (2023) provided a summary of the data from the 2013 decadal survey, data from the 2023–2032 planetary science and astrobiology decadal survey (NASEM 2022c), and data from the astronomy and astrophysics decadal survey (NASEM 2023b), in addition to data regarding physics degree recipients. The study highlighted some of the key data needed to understand demographic trends in physics, which can inform the community, but it emphasized the differences between physics and the subfields of space science that only solar and space physics–specific studies can address.

Unfortunately, only a limited number of specific studies have been done on solar and space physics, despite a clear recommendation made in the midterm assessment (Recommendation 6.2 in NASEM [2020]). Assessing the current state of the profession is difficult due to the lack of a common identity for the field. This lack of a common identity hinders the compilation of important data, such as the size of the community, its demographics (e.g., gender, race, ethnicity, job descriptions—such as tenure and tenure track and soft money research scientists), career stage, funding levels, and research productivity (including papers, patents, and citations). Individual professional societies, federal agencies, universities, research communities—such as the NSF Geospace Environment Modeling (GEM); Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR); and Solar, Heliospheric and Interplanetary Environment (SHINE) communities—and national laboratories have begun efforts to compile these data and conduct the needed surveys, but there has not been an effort to accomplish this specifically for the solar and space physics community since the 2013 decadal survey.

The most complete demographic data and preliminary culture survey data of the broad solar and space physics community, which grew out of the 2013 decadal survey, are presented here. The methodology, survey, and raw results can be found at Moldwin and Morrow (2021), but the panel notes that these data were only recently made accessible and are now more than 10 years old. This panel report also provides more limited data from NASA, the AGU Space Physics and Aeronomy (SPA) section, and the NSF CEDAR and GEM communities, as well as other studies, but emphasizes that these are snapshots in time and reflect only subsets of the solar and space physics

[1] This paragraph was modified after release of the report to accurately reflect NASA’s antiharassment policy.

community. The studies also do not necessarily use the same categories for gender, race, and ethnicity and have had varying degrees of participation.

As part of the 2013 decadal survey process, the Education and Workforce Working Group developed a community survey that was implemented by the American Institute of Physics (AIP) and funded by an NSF grant. The goals of the survey were to determine the demographics of the field and assess the health of the field. The survey request was sent to 2,560 unique email addresses from the AGU SPA, the American Astronomical Society (AAS) Solar Physics Division (SPD), Space Weather Week attendee lists, and NSF PI lists. A total of 1,305 responses (51 percent) were received, of which 1,171 indicated that they considered themselves in the field of solar, space, and upper-atmospheric physics and currently work and reside in the United States. The survey generated 125 pages of single-spaced responses to several open-ended questions. These responses have not yet been systematically analyzed, so this summary of the report is preliminary and focuses on demographic statistics (Moldwin and Morrow 2021).

Of the respondents, 83 percent were men and 17 percent women. Most were White (81 percent), 13 percent were Asian or Asian American, and 6 percent other. The median age of the respondents was 51 years old with a symmetric distribution (the middle 50 percent were between 40 and 62 years old). Physics was by far the most common undergraduate degree (62 percent). For those earning their PhDs in 1999 or earlier, physics was the most common degree field (40 percent), while the most common degree for those receiving PhDs since 2000 was space physics (36 percent, while physics dropped to 27 percent). Almost three-quarters of graduate student support and two-thirds of undergraduate student research support is from NASA or NSF. Nearly three-quarters of those who received their PhDs since 2000 participated in some form of undergraduate research. About half of the respondents reported that they were involved at some level in K–12 education or public outreach.

The survey asked several Likert-scale questions (which offer several options for responses) with the opportunity to elaborate on their answers—two of which are highlighted here. One question asked if they strongly agree, agree, disagree, strongly disagree, or "don't know" regarding the following statement, "The next generation of scientific leadership is emerging in my field, and I am confident that they will be able to answer the scientific questions of the next decade." Two-thirds of the respondents agreed or agreed strongly with the statement, while one-quarter disagreed or disagreed strongly. The open-ended comments were generally optimistic about the abilities of the next generation, but pessimistic about reduction in funding and NASA missions. Another question asked, "What have been the barriers to your career up until this point?," and the responses were divided between men and women. Over 31 percent (48 of 154) of the written responses from women indicated some form of gender discrimination or lack of family-friendly policies as barriers.

The 2013 decadal survey also compiled the number of job advertisements posted in the AGU SPA and the AAS SPD newsletters for postdoctoral (postdoc), research scientist, and faculty positions in addition to the number of new PhDs granted each year in solar and space physics from North American universities (Moldwin et al. 2013). An alarming finding was that in 2010 (just into the great recession of 2008–2009), global postdoc, research scientist, and faculty job ads fell to the lowest levels in the decade (and for faculty positions to just 7 from the typical 15–25 per year from 2001 to 2009). The big questions raised by Bagenal (2023) were, "What has happened in the past decade? Have the trends . . . persisted or changed?" Below, these questions are partially addressed with new analysis for 2010–2020.

Figure F-2 shows the number of job ads for (a) postdocs, (b) research scientists, and (c) tenure and tenure-track faculty and includes data from the 2013 decadal survey for context along with data from the 2011–2020 update. The data are divided between positions in the United States and international positions. The numbers rebounded in 2015 and for faculty, moved back to the 20-per-year range seen in the previous decade. It seems clear that the recommendation supporting the NSF Faculty Development in Space Sciences (FDSS) program has helped significantly since the publication of the previous decadal survey, with 18 new assistant professor faculty hires made through this program and a new funding cycle just announced.

Since 2016, the number of advertisements in all three positions have reached all-time highs. However, absent a quantitative census to determine the size of the field it is impossible to say whether these increases are sufficient to keep pace with growth of the discipline. The methodology used for the 2011–2020 data is identical to that used in Moldwin et al. (2013), and the new data are available in Moldwin (2023).

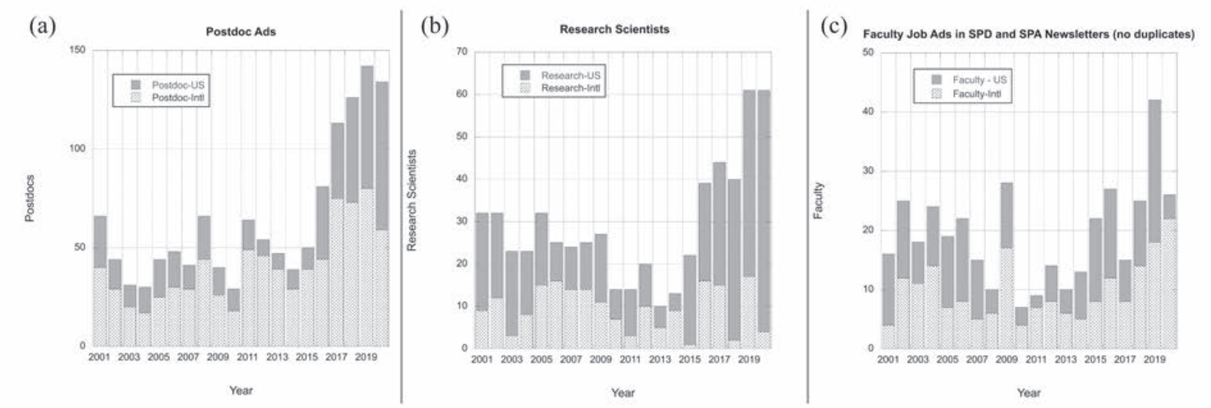

FIGURE F-2 Number of job advertisements for (a) postdocs, (b) research scientists, and (c) tenure and tenure-track faculty divided between U.S. and international institutions.
NOTES: The figure includes data from the 2013 decadal survey (NRC 2013) for context, along with data from the 2011–2020 update. SPA, Space Physics and Aeronomy (section of the American Geophysical Union); SPD, Solar Physics Division (of the American Astronomical Society).
SOURCE: Based on data from Moldwin (2024), https://doi.org/10.7302/fpp2-pc60. CC BY-NC 4.0.

From 2016 to 2021 the SPA primary AGU membership (3,600) and total (5,600) membership[2] was steady. The AGU SPA primary section affiliation membership in 2021 was 23.9 percent women, compared with 33 percent of all AGU members, 35 percent of planetary scientists (Bagenal 2023), and 17 percent women in the previous decadal survey snapshot taken in 2013. In 2017, 31 percent of AAS members were women (Pold and Ivie 2019). Taken at face value, the solar and space physics community as represented by AGU SPA membership demographics has made progress in representation of women (from 17 to 24 percent), but women are still underrepresented in comparison with the broader Earth and space science community and with other space science disciplines.

The NSF CEDAR community has begun to ask demographic questions for workshop attendees and the data provide a comparison with the previous decadal survey data, the more recent AGU SPA demographic breakdown by gender and career level (AGU 2018), and the *Advancing Diversity* report (NASEM 2022). In 2021, 28 percent of the CEDAR registrants gender identified as she/her, while 58 percent identified as he/him. The questionnaire also gave the option of "non-binary" (1 percent) and "no response" (13 percent). In general, these studies reported women or the gender identity of she/her of approximately 30 percent (±10 percent) of student and professional populations in AGU SPA, as well as those serving as PIs or co-investigators (Co-Is) in heliophysics research and analysis proposals submitted to the NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES) between 2014 and 2020. However, comparing CEDAR gender demographics as a function of career stage is quite difficult given the lack of consistent demographic collection across heliophysics—a common theme noted in several recent National Academies reports cited herein.

With respect to race and ethnicity, CEDAR attendees in 2021 were 56 percent White, 35 percent Asian, and 9 percent other. Underrepresented minority registrants in STEM fields represented 9–12 percent of all registrants for the CEDAR workshops in 2021 and 2022. While CEDAR demographic data generally show that earlier career participants tend to be slightly more diverse than those at mid- and senior career levels, the 12 percent or less of minority representation falls below the noted 15 percent participation level cited by Cain and Leahey (2014) as an important benchmark for realizing the benefits of diversity in groups. However, the underrepresented participants in recent GEM workshops for 2020–2022 have seen a steady increase from 14–30 percent, with declining numbers of participants choosing "prefer not to answer." This is encouraging news and raises an interesting key question: Is there a causal relationship between reporting of underrepresented participations, PIs, Co-Is, other invested parties, and other designations and choosing "prefer not to answer" to demographic questionnaires and surveys?

[2] AGU allows members to indicate primary sections and multiple other section affiliations, such as planetary, atmospheric, or education.

The panel also notes that in 2021 the CEDAR community had a significantly higher proportion of Asians than the proportion identified in the 2013 solar and space physics demographic survey data: see Figures F.3, F.4, and F.5. Figure F-6 shows data from recent GEM workshops. These data raise another interesting question: Is CEDAR representative of the overall community or do the data simply reflect year-to-year fluctuations in attendees? Again, this question further highlights the need for regular and consistent collection of, as well as transparent reporting of, demographics in the solar and space physics community.

CEDAR, GEM, and SHINE are programs funded by the NSF Division of Atmospheric and Geospace Sciences Division under the Directorate for Geosciences. The demographics from the recent CEDAR and GEM workshops represent subsets of the solar and space physics community; this type of demographic collection by such programs are new, grassroots efforts that need to continue. However, demographic information from proposals solicited by NSF and NASA, two of the major funders of solar and space physics education, research, and infrastructure, are starting to emerge in either the peer-reviewed literature or published by the agencies themselves and offer a view into the current state of the profession.

A fairly extensive demographic study by Chen et al. (2022) investigated the trends in NSF funding rates from 1996 to 2019, paying specific attention to race and ethnicity: see Figures F-7 and F-8. While Chen et al. (2022) looked at NSF trends in funding rates only down to the directorate level, some important trends were revealed. The number of proposals submitted to Geosciences Directorate at NSF steadily declined between 2012 and 2016, while the number of awards remained fairly constant, and overall funding rates ranged between ~25 and 30 percent.

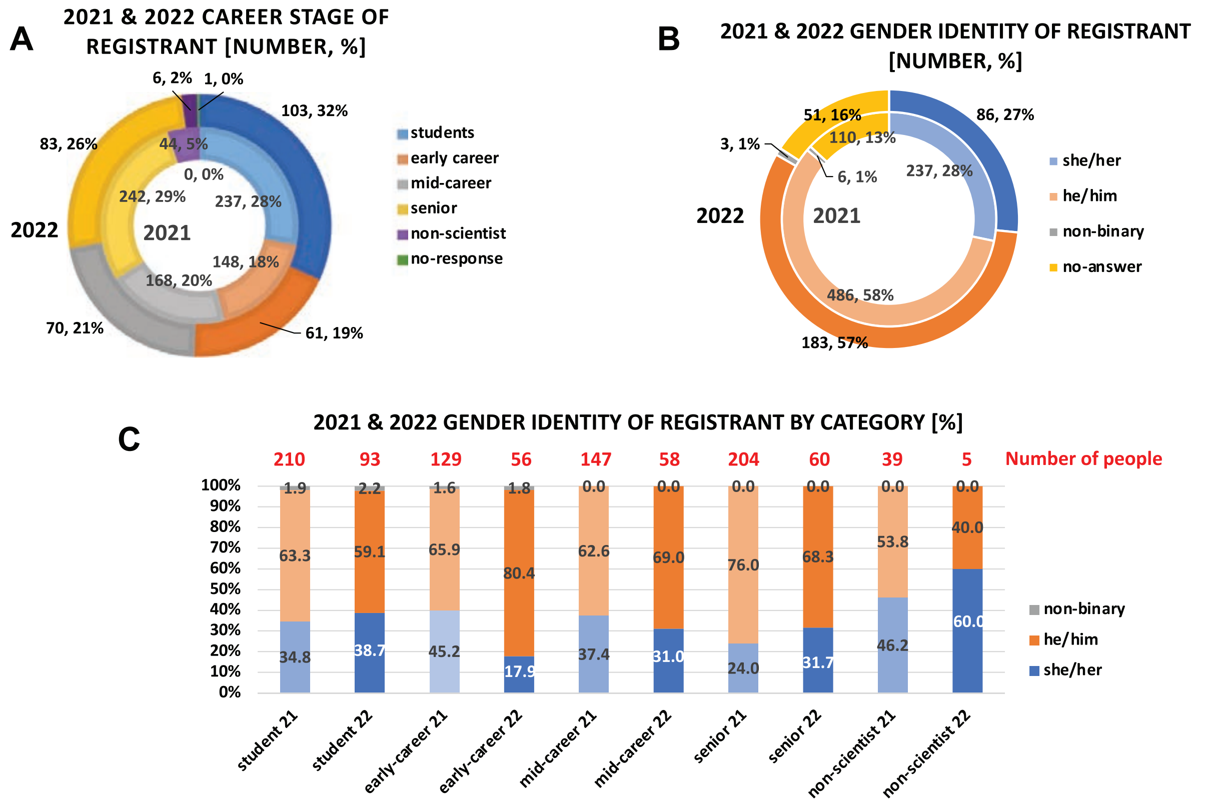

FIGURE F-3 Career stage distribution and gender identity distribution of registrants for annual CEDAR workshops, 2021 and 2022.
NOTE: CEDAR, Coupling, Energetics, and Dynamics of Atmospheric Regions.
SOURCE: Jones and Maute (2022), https://www.frontiersin.org/articles/10.3389/fspas.2022.1074460/full. CC BY 4.0.

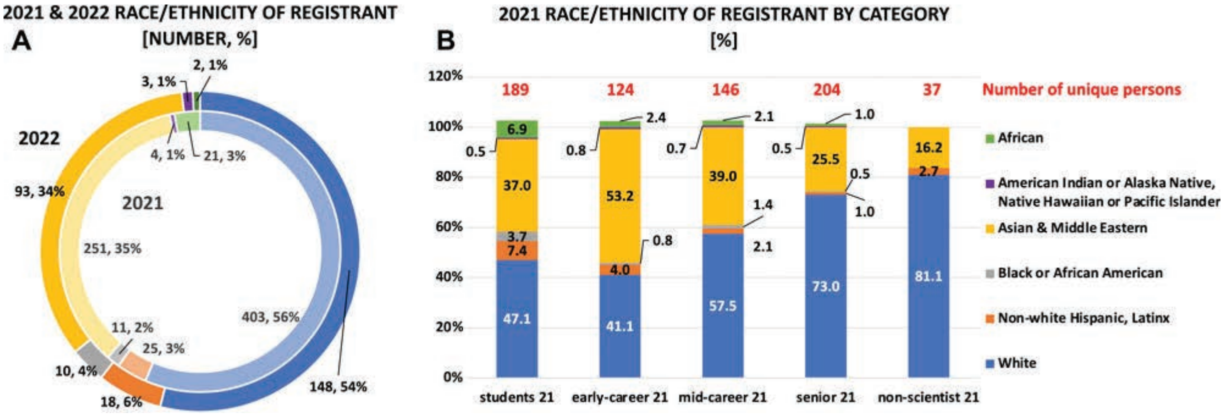

FIGURE F-4 Race and ethnicity of registrants for annual CEDAR workshops, 2021 and 2022.
NOTE: CEDAR, Coupling, Energetics, and Dynamics of Atmospheric Regions.
SOURCE: Jones and Maute (2022), https://www.frontiersin.org/articles/10.3389/fspas.2022.1074460/full. CC BY 4.0.

Other striking results show that the proposals (both research and nonresearch) submitted to the NSF Geosciences Directorate were overwhelmingly from White PIs for 2012–2016, some 20 percent higher than reported by the NASA Heliophysics Division for 2014–2020. Also, Asian and Hispanic/Latino PIs submitting proposals to the NSF Geosciences Directorate saw a funding award deficit (i.e., funding rates below overall directorate funding) for 2012–2016; see Figure F-7. Such racial disparities in funding are concerning; repeating a Chen et al. (2022) study at the NSF divisional level, specifically the Atmospheric and Geospace Sciences, is needed to understand funding rates and trends for most of the solar and space physics community. With about 5,000 proposals per year

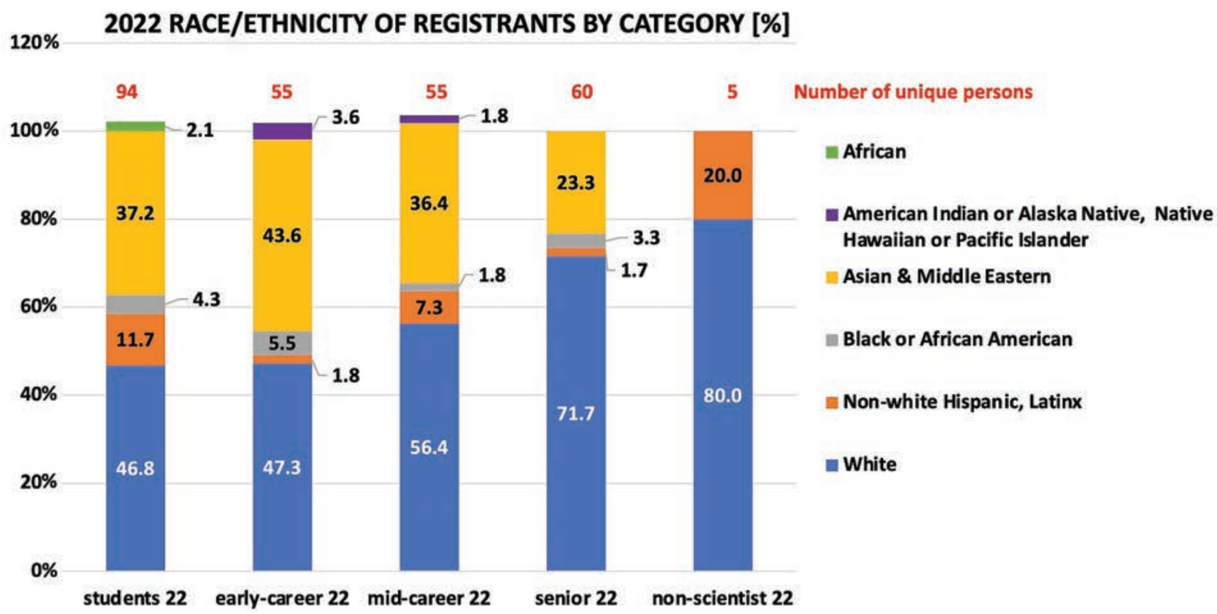

FIGURE F-5 Race and ethnicity of registrants by category for the 2022 CEDAR workshop.
NOTE: CEDAR, Coupling, Energetics, and Dynamics of Atmospheric Regions.
SOURCE: Jones and Maute (2022), https://www.frontiersin.org/articles/10.3389/fspas.2022.1074460/full. CC BY 4.0.

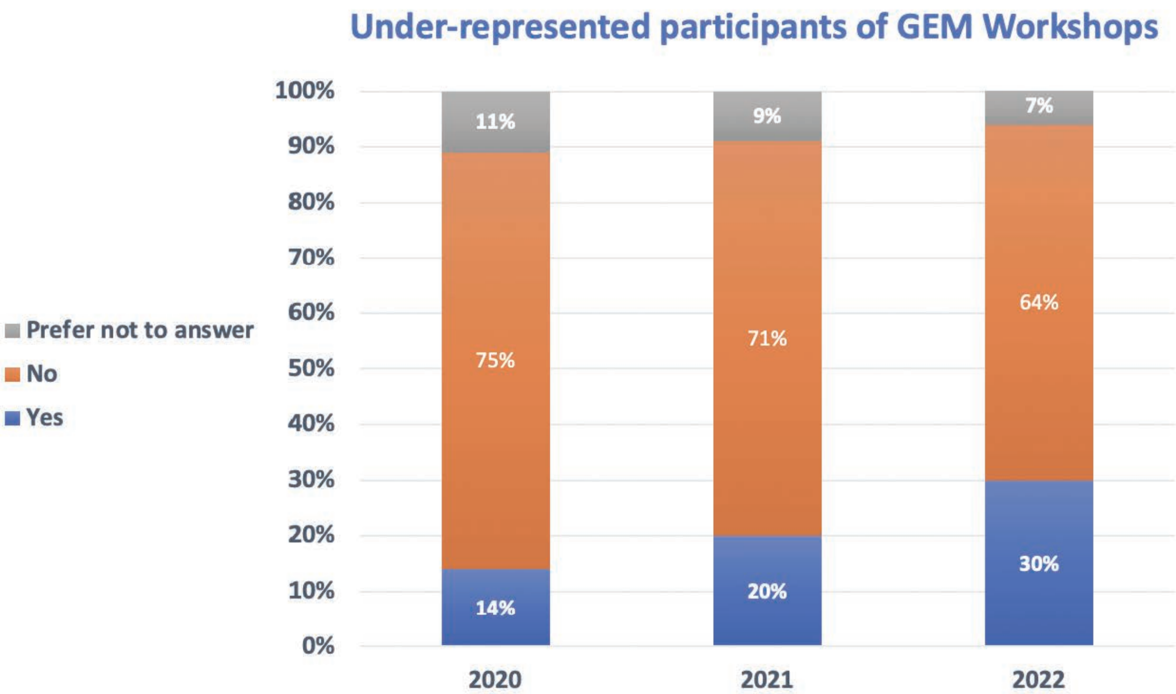

FIGURE F-6 Percentage of underrepresented participants in GEM workshops from 2020 to 2022.
NOTE: GEM, Geospace Environment Modeling.
SOURCE: Huang (2023).

(of which about 600 and 200 per year submitted by investigators who identify as Asian and Hispanic, respectively) the award surplus or deficits and differences between relative funding rates by race for the most part are statistically significant.

Chen et al. (2022) also reported another concerning trend regarding the nonreporting of demographic information from 1999 to 2020. The percentage of proposals submitted by PIs to NSF who provided information on their gender, race, or ethnicity drastically dropped between 1999 and 2020: see Figure F-8. The authors also reported that this trend is accelerating and reported that there was a 10 percent drop in the response rate between 2019 and 2020 alone. The cause of such a drop and prevalence at the directorate and division level is unknown, and it is somewhat at odds with CEDAR and GEM demographic information (detailed above). Nonetheless, such a trend in "prefer not to answer" responses, if present in the Atmospheric and Geospace Sciences Division, needs to be addressed. One suggestion is to clearly articulate the value of the data and emphasize that it is not used in the selection process; this could help increase participation.

In 2023, the NASA Office of the Chief Scientist released the NASA Researcher Demographics Report (NASA 2023), summarizing the demographic data collected by NASA's Science Mission Directorate (SMD) for 2014–2020. These data were collected voluntarily through the NSPIRES web portal used to respond to announcements of opportunity, Research Opportunities in Space and Earth Science (ROSES) proposal solicitations, mail-in panel reviews, and student fellowship opportunities. Demographic data collected from NASA announcements of opportunity were reported only at the SMD level, while demographic data collected from ROSES PIs and Co-Is were presented at the division level. Therefore, the panel summarizes below the salient demographic data collected on ROSES PIs and Co-Is for proposals submitted to the NASA Heliophysics Division. Note that this includes only a fraction of all the information detailed in the *NASA Researcher Demographics 2023 Report*, and it is strongly suggested that the solar and space physics community review the full NASA report for more details.

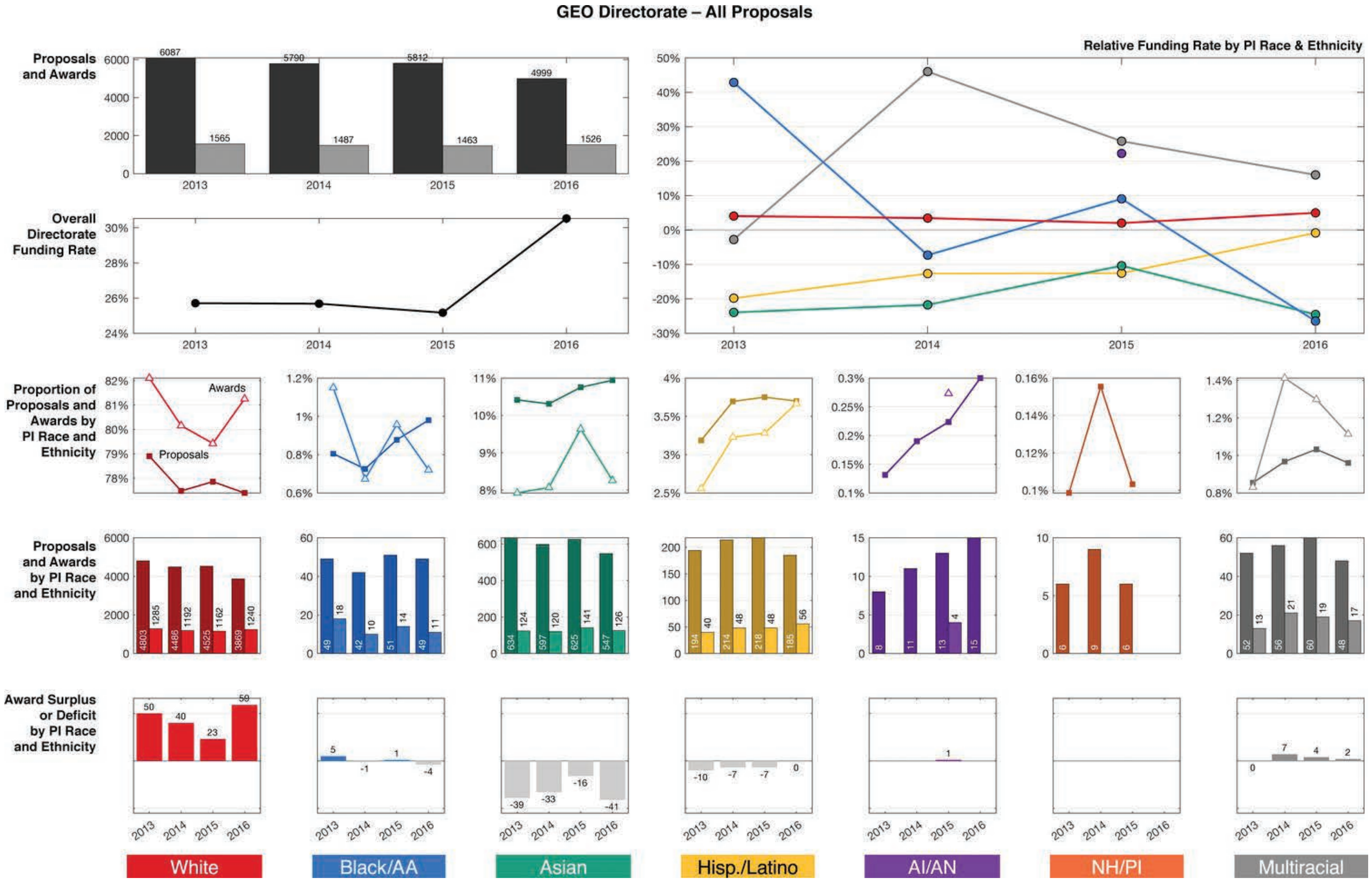

FIGURE F-7 Funding outcomes by PI race and ethnicity for all proposals in the NSF Directorate for Geosciences (GEO) for 2012–2016.
NOTE: AA, African American; AI/AN, American Indian/Alaskan Native; NH/PI, Native Hawaiian/Pacific Islander; NSF, National Science Foundation; PI, principal investigator.
SOURCE: Chen et al. (2022). CC0 1.0.

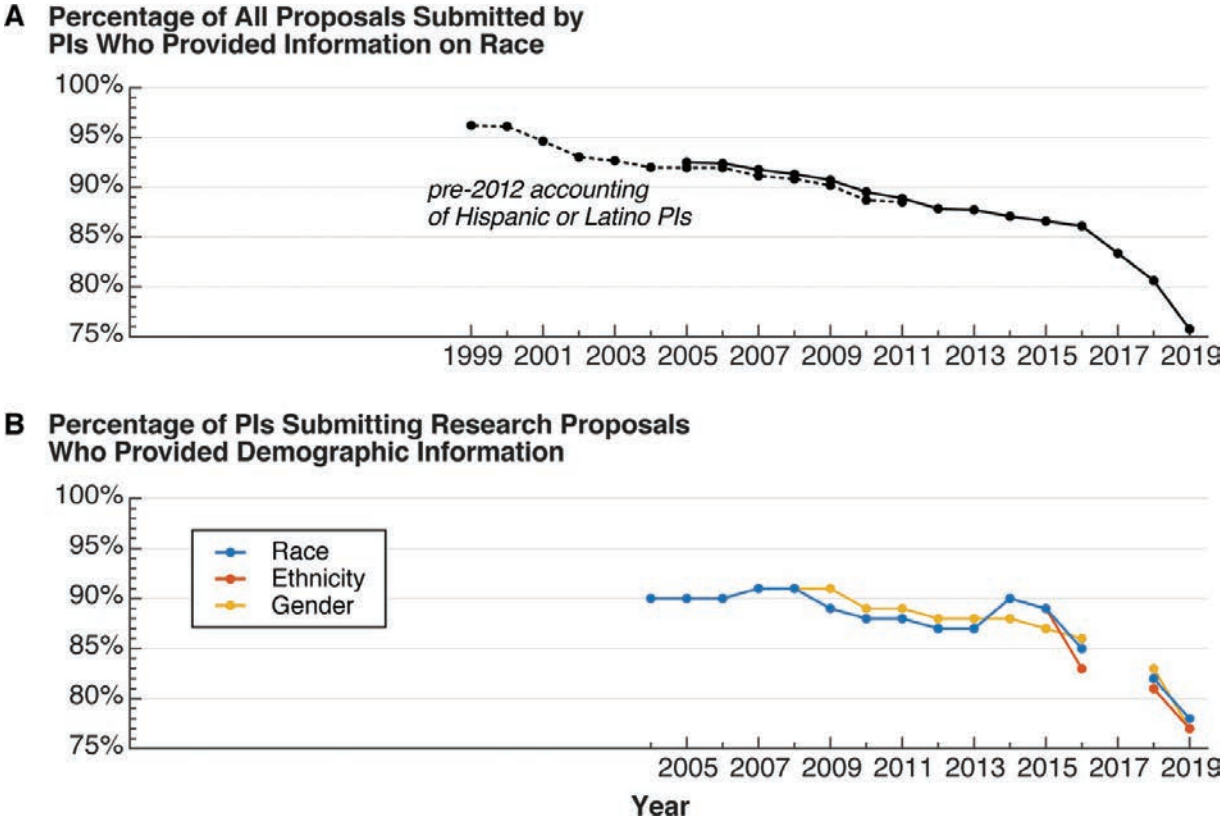

FIGURE F-8 Trends in the nonreporting of demographic information by principal investigators (PIs) from 1999 to 2019.
NOTES: The solid line in Panel A represents data from 2005 to 2019 (National Science Foundation Merit Review Reports after and including 2012), where individuals self-identifying as a particular race are included regardless of their race or their ethnicity (non-Hispanic, Hispanic, or unknown). The dashed line represents data from 1996 to 2011, where individuals are only included in a particular race category if they are non-Hispanic.
SOURCE: Chen et al. (2022). CC0 1.0.

The majority of proposals submitted to ROSES solicitations in heliophysics were submitted by individuals identifying as male, with percentages ranging from 67 to 71 percent for 2014–2020: see Figure F-9. Roughly 70 percent male representation of ROSES PIs and Co-Is in heliophysics is broadly consistent with the AGU SPA membership numbers reported in 2018 (AGU 2018) and those from CEDAR workshop data for 2021 and 2022 (see above). Submissions by female PIs and Co-Is range from 17 to 21 percent over the 7-year period studied by NASA. “Prefer not to answer” responses from PIs and Co-Is represented between 11 and 16 percent of ROSES submissions. Of note is the weak downward trend in the “prefer not to answer” category, which is encouraging and opposite of those reported by Chen et al. (2022) for NSF. Also encouraging from the *NASA Researcher Demographics 2023 Report* is that success rates for proposals submitted to the NASA Heliophysics Division appear to be increasing. With such a short time series, it is hard to assess gender disparities for funding success rates; continued demographic data collection would facilitate analyses of this kind.

Most PIs and Co-Is submitting proposals in response to NASA ROSES solicitations in Heliophysics identify as White, ranging between ~50 and 60 percent for 2014–2020. The next largest group of PIs and Co-Is selected “prefer not to answer,” representing 21 percent of all proposals submitted between 2014 and 2020, with values ranging from 18 to 24 percent. These data raise the question of why solar and space physics applicants are selecting “prefer not to answer” at this high rate, one that requires further probing over the next decade.

The remaining PIs and Co-Is submitting to ROSES solicitations in Heliophysics identified as Asian (16 percent) or Hispanic (3 percent); those identifying as Black and or “race not listed” accounted for less than 1 percent

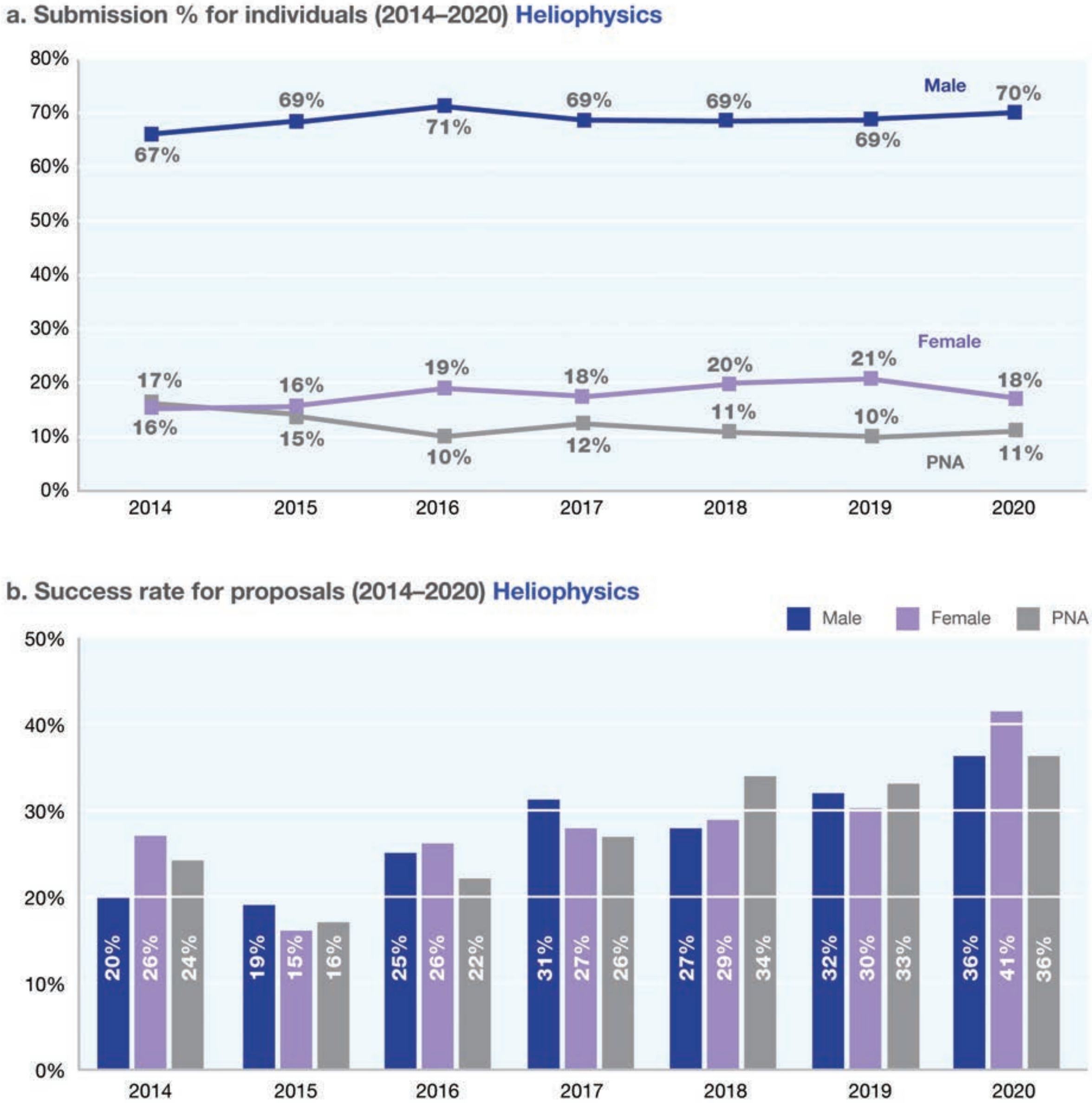

FIGURE F-9 NASA Research Opportunities in Space and Earth Science submissions and success rates for proposals submitted to the Heliophysics Division by gender from 2014 to 2020.
NOTE: PNA, prefer not to answer.
SOURCE: NASA (2023).

of the proposals. Such a very low number of proposals submitted to ROSES solicitations in heliophysics by those who indicated that they are underrepresented minorities, coupled with the data for the participation numbers in CEDAR and GEM, is some of the best evidence on the lack of diversity in the field and requires action.

Success rates for all proposals submitted to NASA ROSES solicitations in Heliophysics for 2014–2020 were between 23 and 27 percent. Proposals with PIs and Co-Is identifying as White had a slightly higher success than those whose PIs and Co-Is identified as Asian, Hispanic, or chose not to answer these demographic questions (as shown in Figure F-10). The success rates for PIs and Co-Is identifying as Black and "race not listed" are not shown in in Part B of Figure F-10 because those PIs and Co-Is accounted for less than 1 percent of all proposals submitted.

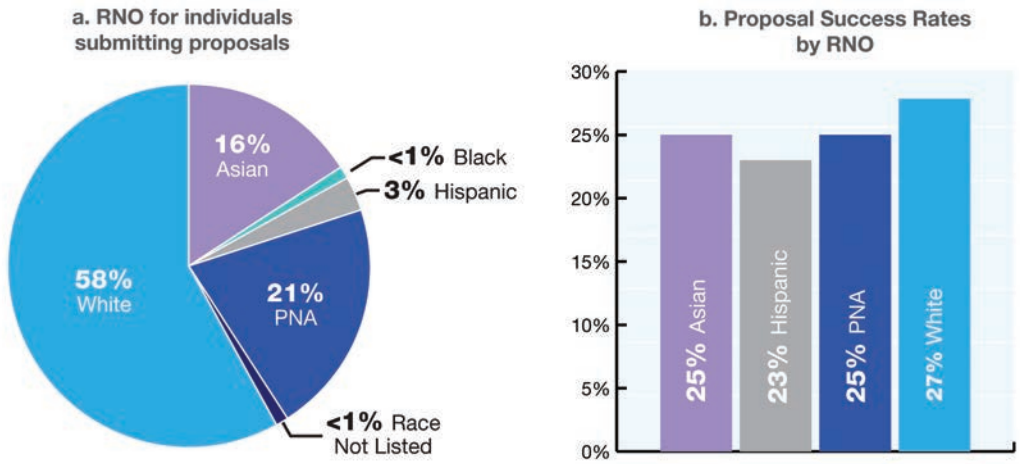

FIGURE F-10 NASA Research Opportunities in Space and Earth Science submissions and success rates for proposals submitted to the Heliophysics Division by race and national origin for the 2014–2020 years combined.
NOTE: PNA, prefer not to answer.
SOURCE: NASA (2023).

The *NASA Research Demographics 2023 Report* (NASA 2023) states: "There are too few Black individuals in Heliophysics to allow reporting, so their success rate is unknown at this time" (p. 39). Even though the percentages of all proposals submitted from PIs and Co-Is identifying as Black and "race not listed" are extremely small, having the actual number of proposals submitted by these groups is nonetheless important to evaluate the state of the profession. Of note is the fact that proposal success rates for White PIs and Co-Is are slightly higher than all other groups for 2014–2020 for Heliophysics and 4 percent higher than Hispanic PIs and Co-Is, which may suggest an award surplus and deficit for such PIs and Co-Is, respectively, following the Chen et al. (2022) definition (i.e., funding rates above overall division level). However, an award surplus or deficit among the different race and national origin demographic categories reported in Figure F-10 is difficult to assess given the percentage of individuals selecting "prefer not to answer." Furthermore, a direct comparison of funding award surplus or deficit between the NASA and NSF results found by Chen et al. (2022) cannot be done because the NASA report did not include the total number of proposals submitted or funded. In addition, the year-to-year data presented by NASA on funding success rates do not include Hispanic or Black data due to the small numbers.[3]

As part of the *NASA Researcher Demographics 2023 Report*, NASA SMD reported data for applicants with disabilities, and those data are extremely encouraging: see Figures F-11 and F-12. Across all years, roughly 3 percent of all PIs and Co-Is submitting proposals to NASA ROSES Heliophysics solicitation identified as having a disability. The "prefer not to answer" responses for race and national origin slightly decreased over time. With only 4 years of reported data, it is hard to see any trend in proposal success rate for PIs and Co-Is who identified as having a disability, but those funding rates were generally between 27 and 30 percent in the available data.

Both Chen et al. (2022) and the NASA demographics report state that limitations in the available data reported make it very difficult to evaluate, understand, and compare demographic information. For example, there were reports that the lack of publicly available data from NSF precludes multivariate and intersectional examinations of NSF racial funding rates alongside other factors, such as gender, career stage, and institution type (Chen et al. 2022). Lack of data access also makes it difficult to examine additional factors that affect funding rates, such as educational background and training, scholarly productivity, institutional knowledge and support, prior funding success, and mentoring. Furthermore, the NASA demographics report identifies the need for synchronizing

[3] The NASA Researcher Demographics 2023 Report also included success rates for proposals submitted to ROSES in heliophysics, which increased for every race and national origin category recorded for NASA, including PIs and Co-Is identifying as White, Asian, and prefer not to answer. However, success rate trends for 2014–2020 PIs and Co-Is identifying as Hispanic, Black, and race not listed were not provided.

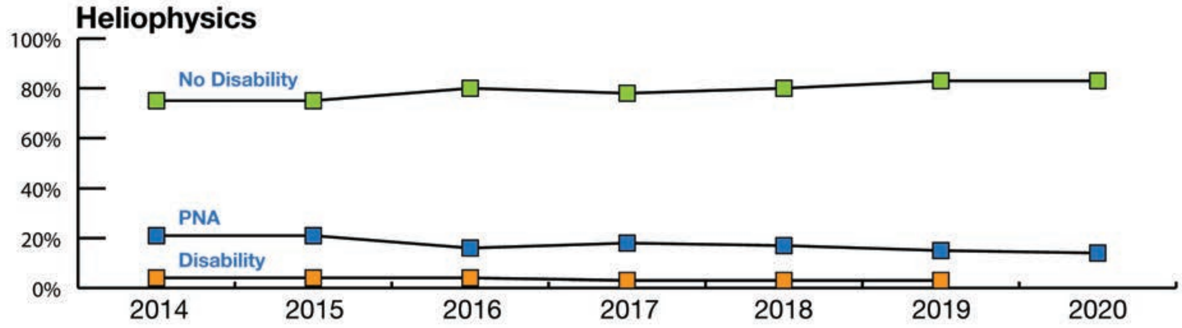

FIGURE F-11 NASA Research Opportunities in Space and Earth Science submissions identified by disability for the Heliophysics Division from 2014 to 2020.
NOTE: PNA, prefer not to answer.
SOURCES: NASA (2023).

demographic surveys between NASA, NSF, AIP, and other relevant organizations to improve the usefulness and intercomparison of demographic information across the STEM enterprise. For example, the discrepant trends between the "prefer not to answer" responses to demographics questions in NSF proposals in 2012–2016 (Chen et al. 2022) and the 2023 NASA demographics report in Heliophysics further highlight this need.

F.4 OVERARCHING GOALS FOR THE NEXT DECADE

By the next decadal survey, the solar and space physics community will become a clearly identifiable community within the space sciences, and, similar to other professional communities (e.g., astronomy), regularly and easily measuring itself and assessing its health and vitality.

FIGURE F-12 NASA Research Opportunities in Space and Earth Science success rate for applicants with a disability to the Heliophysics Division from 2014 to 2020.
SOURCE: NASA (2023).

F.4.1 Identified Barriers

Currently, "solar and space physics" is one of the umbrella terms that encompass the community's different components—that is, the solar, heliospheric, magnetospheric, ionospheric, thermospheric, mesospheric, and space weather communities. Within NASA's SMD, the single-word term "heliophysics" is used and clearly distinguishes it from the Earth science, astrophysics, and planetary science communities.

As highlighted in the 2013 decadal survey, this multiplicity of terms and the "newness" of heliophysics hinders it in communicating its science to other stakeholders, including the public. Other barriers identified by the panel include the following:

- *Lack of unique identity:* Understanding who makes up the current solar and space physics community and the ability to study trends to assess the health and vitality of the discipline continues to be difficult by the lack of a standard name of the discipline within different organizations: solar and space physics (National Academies), heliophysics (NASA), geospace sciences (NSF), space weather (the National Oceanic and Atmospheric Administration [NOAA] and the American Meteorological Society [AMS]), space physics and aeronomy (AGU), solar physics (AAS SPD), and various other permutations within universities. The lack of a common name was raised in the 2013 decadal survey and continues to hinder its ability to articulate its science broadly and assess the state of the profession.
- *Lack of demographic numbers:* Basic demographic data of the solar and space physics community are not available. Broader measures or reporting (such as AIP's surveys of physics and astronomy or NSF's National Center for Science and Engineering Statistics Reports) are not sufficient for understanding the solar and space physics community. Understanding how the climate and culture of the community has changed considering broader societal change is not possible without routine and regular climate surveys. These points have been made by almost every National Academies report focused on culture, climate, and people in the STEM enterprise over the last 2 decades. *The stated goals of the solar and space physics community's institutions and funding agencies regarding improving diversity cannot be taken seriously unless they hold themselves accountable. Accountability is impossible without consistently updated, quantitative demographic and climate data.*

F.4.2 Suggestions

This report numbers each suggestion but they are not ranked ordered. The time frame for when suggested changes are implemented is given as short term, medium term, and long term. These correspond to immediately, by the next midterm assessment, and by the next decadal survey.

1. *A Common Name for the Field* (Medium Term). The panel suggests the community coalesce around a single name—either solar and space physics or heliophysics[4]—in NASA, NSF, NOAA, and the higher education community so that numbers of faculty, researchers, practitioners, and students can be tracked across departments, institutions, professional societies, and employers. Using keywords in ORCID[5] by individual investigators could over time help self-identify the community, especially as having an ORCID identification number is now required by professional societies and funding agencies.

2. *Heliophysics Consortium* (Medium Term). The panel suggests an interagency-funded mechanism (co-led by NASA and NSF with participation of other relevant agencies) to unify the multiple disciplinary subgroups and facilitate networking, collaboration, and communication among them, focusing on integrating and

[4] In the rest of this report, the term heliophysics is included with solar and space physics.

[5] ORCID (Open Researcher and Contributor ID) is a nonproprietary alphanumeric code to uniquely identify authors and contributors of scholarly communication and, on ORCID's website and services, to look up authors and their bibliographic output.

strengthening solar and space physics–heliophysics research and education. This proposed heliophysics consortium would enable:

- Unification of the community message and language, making available education and public outreach–related resources;
- Creation of a community code of conduct and ethics, based on ones developed by AGU;
- Creation of a community message and job board (centralizing, e.g., the newsletters and job advertisements from AGU SPA, AAS SPD, AMS Space Weather, SHINE, CEDAR, GEM, and the Triennial Earth-Sun Summit), as well as the development and active curation of a unified web page similar to the National Space Weather Program Unified Space Weather Portal[6];
- Establishment of a shared graduate application process, including all the higher education programs that offer degrees related to the field (e.g., a common application like the American Physical Society [APS]/AGU Bridge program in which students can indicate that they are willing to have their application considered by multiple institutions); and
- Administration of a community climate survey (following on the 2013 decadal survey) in preparation for the next midterm assessment to help identify the solar and space physics–heliophysics community (e.g., FDSS, NASA Postdoctoral Program, graduate fellowships, AAS SPD, AGU SPA, and AMS participants; higher education institutions; federally funded research and development centers; and other institutions).

3. *Demographics Data System* (Medium Term). The panel suggests that federal agencies systematically and transparently collect, monitor, and analyze demographic data that will better inform what are the barriers and opportunities for career advancements (e.g., NASA could assess gender differences in award rates). The panel also suggests that NASA, NSF, and NOAA work with independent organizations (such as AIP) to conduct regular climate surveys every 5 years of the community and routinely provide proposal and award data to the proposed heliophysics consortium. In addition, professional societies (AGU, AAS, and AMS) could provide data on meeting attendees and journal authors and referees. The proposed consortium could take the lead in developing, implementing, analyzing, and communicating the results of climate surveys and the health and vitality of the community and engage social scientists in crafting the surveys, interpreting the results, and recommending actions. Development of a communitywide (and accessible to the entire community) database can be used to assess demographic trends and provide input to the decadal midterm review to assess the effectiveness of strategies and programs adopted. In addition, to aid the identification of the community and help unify the community under a single name, it would be valuable to use a common keyword on ORCID ID profiles—for example, “#Heliophysics.”

F.5 DEIA+ DIVERSITY, EQUITY, INCLUSION, AND ACCESSIBILITY+

To expand opportunities for new discoveries and to incorporate advanced tools and technologies in a healthy and sustainable solar and space physics community over the next decade, the community has to be more diverse, equitable, inclusive, accessible, anti-racist, accountable, health-promoting, and just DEIA+. The panel uses the “+” throughout the report to highlight that “DEIA” by itself is missing many components—especially accountability. As society is witnessing, DEIA has become the victim of the culture wars and literally outlawed in some states (Burch 2023). Even without the politicization of the acronym, it has often become a “check box” used to highlight efforts without making real progress. Although institutions and society have changed in the wake of the #MeToo movement and George Floyd’s murder by police, too often survivors of sexual assault or harassment are the ones who suffer negative consequences at the hands of their institutions, and implicit and explicit bias and systemic barriers continue to hinder progress.

[6] Note that https://www.swpc.noaa.gov/portal is no longer maintained.

Another aspect of the current research culture is to discount the importance of personal well-being in promoting excellence. Having a health-promoting culture is essential to attract a diverse and talented workforce and to help sustain and enable the solar and space physics–heliophysics community to innovate and make discoveries. Health-promoting is included in the "+" to highlight the importance of well-being (including aspects of mental health, work–life balance, compensation, job stability, and safety) of individuals, teams, departments, universities, and other research institutions. (In addition to the discussion in this section, additional aspects of the issue are covered in the Section F.8, below, on workforce sustainable growth.)

Before presenting DEIA+ goals for the next decade, the panel offers a few observations to help set the stage for the panel's suggestions. These observations are from the social sciences (Cech 2022; Graves et al. 2022; Thomsen 2022) and address concepts and beliefs that have created the current state and hinder efforts at developing a more DEIA+ community. These statements are made to counter arguments that are often made or beliefs that are held that have hindered progress in changing culture.

- Lack of progress is not due to a few "bad apples" but is driven by systemic issues (McDonald 2021).
- Subtle beliefs and practices matter (Offermann et al. 2014).
- Positive change is not inevitable; it requires work (Holvino et al. 2004).
- Dominant group members often do not understand the climate of marginalized people, such as people of color, women, and those who identify as LGBTQ+ (NASEM 2023; Shelton 2013).
- Small advantages and disadvantages accumulate over time—the so-called Matthew Effect[7]: see Figure F-13.
- DEIA+ efforts are not recognized or rewarded as part of the research culture (LeanIn.Org and McKinsey and Company 2021).
- Women and minorities who engage in fixing systemic issues at a much higher rate than dominant group members are often penalized (Johnson and Hekman 2016).
- Quality evaluation and assessment requires resources and collaboration among social scientists and the solar and space physics–heliophysics community (Jones et al. 2022).

F.5.1 Overarching Goals for the Next Decade

An overarching goal is that by the next decadal survey, the solar and space physics (heliophysics) community will have fully adopted leading DEIA+ practices at the individual (especially gatekeeper), institutional, and agency levels. As with all complex, coupled systems, the solar and space physics community system behavior is driven by two-way coupled feedbacks between the components, and therefore mutually reinforcing leading practices and behaviors will have been identified and strengthened. Specifically, the panel's hope over the next decade is that the solar and space physics (heliophysics) community will be one defined by equitable practices and will broaden the definition of research excellence to incorporate inclusion. Rodriguez (2016) defines "equity" as enactment of specific policies and practices that ensure equitable access and opportunities for success for everyone. Equity can be viewed as providing resources and structures that are not equal, but meet people where they are, to ensure that all people can participate in solar and space physics (Pendergrass et al. 2019). Inclusive excellence rewards those who engage and promote broadening participation and inclusive practices that promote well-being and belonging.

F.5.2 Identified Barriers

- *Lack of DEIA+ strategies beyond compliance:* Decades of research has shown that as part of the broader STEM community, solar and space physics–heliophysics is not diverse, equitable, inclusive, accessible, or developing anti-racist and health-promoting strategies to confront structural barriers for full participation. Also, despite significant efforts to address these shortcomings, little progress was made in the last decade in the solar and space physics–heliophysics community.

[7] The Matthew Effect (Merton 1968) is the tendency of individuals to accrue advantages in proportion to their initial level of success and takes its name from the Parable of the Talents in the biblical Gospel of Matthew.

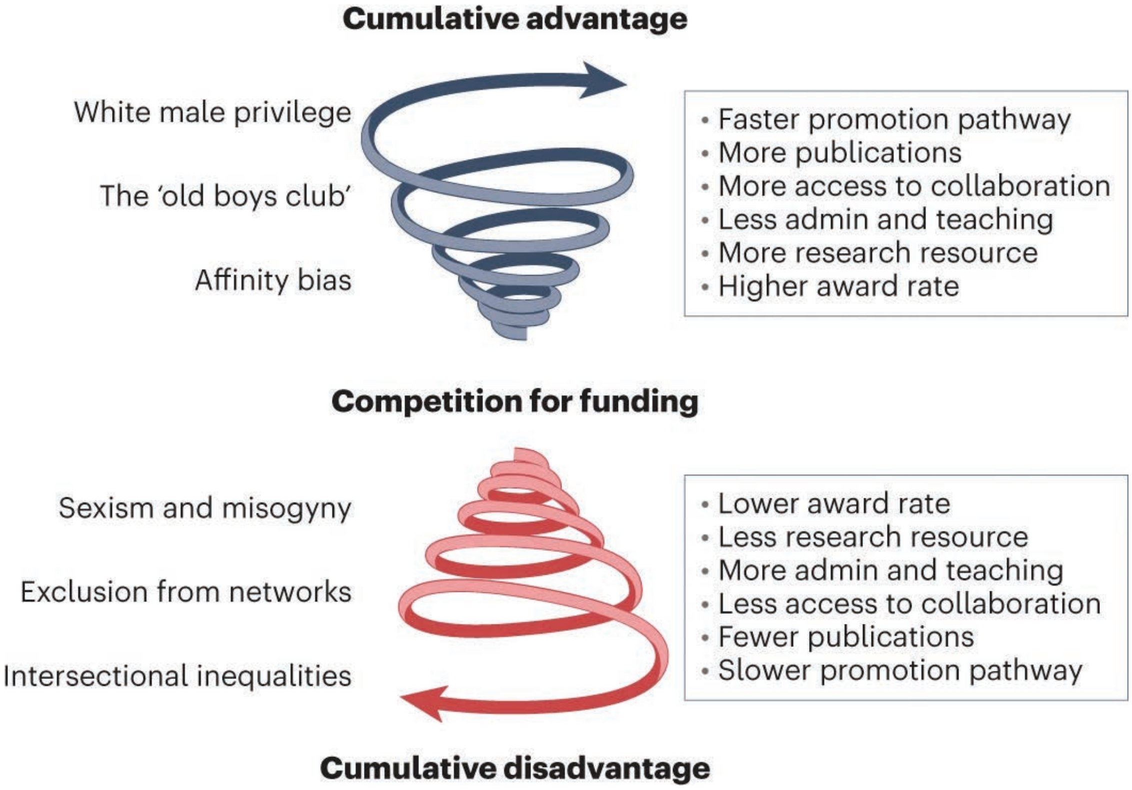

FIGURE F-13 How small disparities due to bias and systemic barriers can lead to large cumulative advantages and disadvantages. SOURCES: J.M. Jebsen, K. Nicoll Baines, R.A. Oliver, and I. Jayasinghe, 2022, "Dismantling barriers faced by women in STEM," *Nature Chemistry* 14:1203–1206, Springer Nature.

- *DEIA+ barriers by individual states:* Several states have passed or are considering bans in state-funded DEIA+ initiatives. As NASA and NSF have components of awards dependent on DEIA+ plans and other, broader impacts following the President's Executive Order (Biden 2021) and agency strategic initiatives, the state bans are creating confusion among the solar and space physics community.
- *Lack of well-being:* A culture that does not promote safe workplaces for all and work–life balance, provide clear pathway options for stable careers, support working parents, or provide a livable wage for many students and early career professionals is not healthy or sustainable.

F.5.3 Suggestions

As noted above, the panel's suggestions are numbered but not rank ordered, and they are identified as short term (immediate), medium term (by the next midterm assessment), or long term (by the next decadal survey).

4. *Committees with DEIA+ Subject-Matter Experts* (Short Term). The panel suggests that NASA, NOAA, NSF, and the solar and space physics–heliophysics institutions create or continue committees with DEIA+ subject-matter experts. NASA, NOAA, and NSF continue to hire and fund DEIA+ subject-matter experts to integrate relevant teams, organizations, and committees in the agency to:

   - Map structural, organizational, individual bias, inequalities, and racism in solar and space physics–heliophysics funded activities;
   - Understand the role of leadership and organizations in propagating the issues;

- Create roadmaps and metrics to improve DEIA+ in heliophysics; and
- Evaluate gatekeepers' and organization's programs, policies, and practices in an effective way (e.g., using NIH as an exemplar).

5. *DEIA+ Plans for Large Team Proposals* (Short Term). The panel suggests that NASA and NSF require DEIA+ plans for large team proposals and that they be included as an evaluation factor. Proposal review panels would include DEIA+ experts or trained reviewers to properly evaluate a required DEIA+ plan (i.e., NSF broader impacts and NASA IDEA [inclusion, diversity, equity, and accessibility] plans). Resources regarding DEIA+ best practices and how to develop strong accountable plans could be provided to proposing teams. The plans would be evaluated and be part of the overall proposal evaluation.

6. *Educating the Solar and Space Physics–Heliophysics Community on DEIA+'s Importance* (Short Term). The panel suggests NSF and NASA support efforts on educating the solar and space physics–heliophysics community on DEIA+'s importance. For example, the NSF could provide coordination across SHINE, GEM, and CEDAR to support and fund workshops and professional development opportunities at the workshops around DEIA+. This would include training and support for involving local communities in any fieldwork or infrastructure development.

7. *Policy Changes That Enable Accountability for DEIA+ Efforts* (Medium Term). The panel suggests that NASA, NOAA, NSF, and solar and space physics–heliophysics institutions implement policies that enable accountability for DEIA+ efforts. Funding agencies, recipient universities, institutions, and PIs ought to be held accountable for ensuring that the approved DEIA+ plan is implemented. The survey-sponsoring agencies would monitor compliance with approved DEIA+ plans and take appropriate actions in cases of noncompliance (this could include withdrawal of a current grant to denial of a grant renewal). Mechanisms for anonymous 360-degree evaluations of the team could be included to reduce power differentials and increase the validity of the assessments.

8. *Core Values of Health Promotion* (Medium Term). The panel suggests that as part of the core value of health promotion held by NASA, NOAA, and NSF, those organizations raise undergraduate and graduate student stipend and postdoc researcher salary minimum requirements to a livable wage adjusted by location (e.g., locality-adjusted General Schedule pay) and be reviewed annually. Levels at or above these minimums to be a requirement for programs (such as NSF Research Experiences for Undergraduates [REUs], NASA Future Investigators in NASA Earth and Space Science and Technology [FINESST], or AGS postdocs) and individual investigator grants funded through such programs as NSF GEM or NASA ROSES. Solar and space physics community institutions and funding agencies need to have health promotion at the center of their mission. The Okanagan Charter adopted by many research universities is a model (International Conference on Health Promoting Universities & Colleges, 2015).

F.6 RESEARCH CULTURE

Research culture is difficult to assess, can be different for different individuals, and it is not included in traditional metrics of "health and vitality" of an individual, team, department, or institution. The goal of this panel report is to recenter and reframe the discussion around the people who make up the profession. People interact with each other through shared structures, values, and ideas of excellence and fairness. These cultural norms, schema, and beliefs were created and are propagated by the community, which has been, and is still, majority White, cisgendered, able-bodied, heterosexual men (Bagenal 2023).

F.6.1 Overarching Goal for the Next Decade

By the next decadal survey, the solar and space physics community will be fully centered on people in the profession and recognize that the diversity of identities, backgrounds, cultures, education, and experiences is a strength. This goal includes the creation of programs and policies to enable a healthy and innovative community culture.

F.6.2 Identified Barriers

- *Continued, pervasive sexual harassment, bullying, and discrimination:* There is a lack of straightforward, clear, and anonymous mechanisms to report harassment and abuse, and, once reported, a lack of accountability. Nearly all of this panel's members had experienced harassment due to their gender or race and encountered reporting barriers or institutional pushback. This anecdotal evidence is consistent with results from Funk and Parker (2018) that showed both female and underrepresented minorities (specifically, African Americans) in STEM faced higher rates of discrimination (≥50 percent of the more than 2,300 U.S. adults surveyed in the study), compared with their non-STEM counterparts.
- *Principal investigator power dynamics:* Significant power dynamics are inherent in academia, and research teams and organizations contribute to opportunities for abuse.
- *Lack of support and recognition for those who lead the attraction, retention, and advancement of individuals from underrepresented groups:* To amplify a recommendation from the astronomy and astrophysics decadal survey: there is a need for increased funding and recognition for the people who lead the recruitment, retention, and advancement of individuals from underrepresented groups (NASEM 2023b). This report highlights that those who lead the recruitment, retention, and advancement of those people in STEM, many of whom are themselves from underrepresented groups, take a significant amount of work, time, and energy and often are not recognized or valued as important aspects of their professional responsibilities (Domingo et al. 2022; Hekman et al. 2016; Lerma et al. 2020; Porter et al. 2018). Typically, grants supporting this work (e.g., REUs) have rigid requirements and do not acknowledge the sacrifice the leading PIs are making on their own scientific productivity.

F.6.3 Suggestions

As noted above, the panel's suggestions are numbered but not rank ordered, and they are identified as short term (immediate), medium term (by the next midterm assessment), or long term (by the next decadal survey).

9. *Mechanisms of Accountability of PIs* (Medium Term). The panel suggests that NASA, NOAA, NSF, and other institutions develop mechanisms of accountability of for PIs. Such accounting would include adopting a code of research ethics and conduct (perhaps modeled after AGU or those of other organizations or agencies) for individual laboratories and teams. In addition, the panel suggests that policies be developed that prevent PIs who have had disciplinary findings of research misconduct from obtaining or taking grants to new institutions (i.e., the "pass the abuser" issue).

10. *Ombudsperson to Receive Anonymous Complaints* (Medium Term). The panel suggests that NASA, NOAA, and NSF provide an ombudsperson to receive anonymous complaints and reports from grantees and contractors and adopt mechanisms to hold accountable any people found to have violated codes of conduct. NIH is an example of providing an ombudsman to all stakeholders (NIH employees, contractors, grantees, students, and trainees), as well as providing annual reports on violations.

11. *Mechanisms to Address Issues of Power Dynamics* (Medium Term). The panel suggests that NASA, NOAA, and NSF programs create mechanisms to eliminate or reduce the effects of unequal power dynamics. This could be accomplished by providing funds directly to students (as done with NSF graduate fellowships) and early career professionals (such as postdoc and early career investigators). The programs could provide training for, and assessment of, PI mentoring of students and postdoc and assessment of departments for adopting leading practices around mentoring: one example is the American Association for the Advancement of Science's Sea Change.[8]

[8] See American Association for the Advancement of Science, SEA Change, https://www.aaas.org/programs/sea-change.

12. *Support and Reward Those Who Lead Community Efforts* (Medium Term). The panel suggests that NASA, NOAA, and NSF support and reward those who lead community efforts that sustain a healthy solar and space physics–heliophysics community. Following a suggestion of the astronomy and astrophysics decadal survey, federal agencies could provide material support to researchers who build and lead programs designed to retain, recruit, and advance people from underrepresented minority groups in heliophysics. This approach would expand the community's definition of "excellence" to "inclusive excellence," recognizing and rewarding the value added for these efforts. An example highlighted from that decadal survey report would be to increase the budgets for research grants for those who propose to advance DEIA+ efforts in their institution or the broader community. Funding 5 to 10 grants with an additional $100,000 extra would cost between $500,000 and $1 million per year per agency.

F.7 TEAMWORK

Advancing solar and space physics (heliophysics) research requires teamwork among personnel who possess varying levels of solar and space physics–heliophysics domain expertise and a variety of other high-level skills (including engineering, computer science, mathematics, data science, machine learning, artificial intelligence, meteorology, operations, community building, communications, team science, citizen science, and software engineering). Unfortunately, it is well documented in the social sciences that teams often underperform in terms of their potential due to a variety of "process losses." Moreover, high-profile scientific projects are increasingly tackled by scientific multiteam systems (i.e., interdependent systems of two or more component teams bound together by shared superordinate goals) rather than small stand-alone scientific teams. In comparison with stand-alone teams, multiteam systems offer several benefits, including greater resource capacity and the ability for component teams to specialize and focus on different subtasks. However, the size and scope of multiteam systems often creates additional barriers to teamwork and project management in comparison with stand-alone teams.

The scientific study of teamwork demonstrates that teams and multiteam systems are most likely to be effective when members (1) collaborate rather than compete with one another; (2) coordinate their actions in support of shared goals; (3) develop a shared and accurate understanding of their goals, tasks, and teammates; and (4) feel engaged, motivated, cohesive, and psychologically safe. However, these patterns of behaviors, cognitions, motivation, and affect are not guaranteed. Individual differences play a key role in determining the team processes and psychological states that underpin team and multiteam performance—especially such deep-level characteristics as personality, skills, expertise, and training. Beyond individual differences, research on teamwork demonstrates that a variety of interventions can increase team and multiteam system effectiveness. These interventions include reward systems that reinforce collaborative behaviors, a well-articulated team plan or "charter," functional leadership (i.e., leadership behaviors targeted toward supporting collective goals), team-building activities, teamwork training, frame-of-reference training, systematic and structured debriefing sessions, and assessment systems geared toward understanding and supporting team and system functioning.

F.7.1 Overarching Goal for the Next Decade

By the next decadal survey, the solar and space physics community will have invested in formally training, assessing, and rewarding inclusive and effective teams and multiteam systems by drawing from research on the science of team science as well as the broader science of teams (NRC 2015).

F.7.2 Identified Barriers

- *Team assembly through limited networks:* For many solar and space physics–heliophysics investigations there are difficulties identifying collaborators and assembling teams. For early career investigators, the current mechanisms of team building through "old boy networks" perpetuates inequalities and exclusion (e.g., Case and Richley 2013).

- *Developing teamwork capacity:* Heliophysicist training requires extensive time developing many research skills but devotes significantly less time developing teamwork, communication, leadership, and collaboration skills.
- *Managing large, geographically distributed teams or multiteam team systems:* It is difficult to develop skills and solutions needed for managing and coordinating multiteam system structures, navigating hybrid communication dynamics, having scientists and engineers on multiple teams simultaneously (pulled in different directions), integrating and managing affiliated specialists (such as computer and data scientists), and integrating and developing opportunities for emerging roles (Carter et al. 2019).

F.7.3 Suggestions

As noted above, the panel's suggestions are numbered but not rank ordered, and they are identified as short term (immediate), medium term (by the next midterm assessment), or long term (by the next decadal survey).

13. *Science Team Plans for Mission, Center, and Large Investigations* (Medium Term). The panel suggests that NASA and NSF require science team plans for mission, center, and large investigations. Providing sufficient resources to develop science team plans (i.e., charters, codes of conduct, succession, and communication plans) and making them required for proposals as an evaluated factor would strengthen solar and space physics–heliophysics investigations. Review panels would include team experts or trained reviewers (as was done for the NASA Diversify, Realize, Integrate, Venture, Educate (DRIVE) Center evaluation). Agencies could offer team science planning resources prepared by team experts and pay attention to the level of effort of each member of the team (thinking of efficiency and career impact), how well early career scholars are mentored and trained, and the quality of the succession plan.

14. *Development of Team Science Activities and Curriculum* (Medium Term). The panel suggests that NASA and NSF support development of team science activities and curriculum for the solar and space physics–heliophysics higher education community. Like other important skills needed for success beyond the disciplinary content that traditionally have not been part of graduate educational programs (e.g., written and oral communication skills, research ethics, and open science and data management), NASA and NSF could support the development of materials and curriculum (including online resources) to enable individuals and departments to implement team science training.

F.8 THE SOLAR AND SPACE PHYSICS–HELIOPHYSICS WORKFORCE: SUSTAINABLE GROWTH

The 2013 decadal survey defined the community narrowly by including only those with PhD degrees doing research (Moldwin and Morrow 2016). This panel suggests thinking more broadly about who makes up the community and especially reconsidering the "traditional" pipeline model that neglects the myriad pathways in and out of the community and the broader allied professions that support solar and space physics (heliophysics) endeavors, especially considering the burgeoning commercialization of space and the wide adoption of space technologies into society. Using the braided river model can represent the multiple entry points and pathways and the numerous barriers and opportunities to creating a sustainable and healthy profession: see Figure F-14 (Batchelor et al. 2021).

A common thread throughout the panel's community input papers and direct input to the panel in the public meetings is the need for a workforce of "heliophysics": specifically, a workforce that has varying levels of solar and space physics–heliophysics domain expertise but in tandem with other high-level skills. Examples include engineering expertise; adaptive optics, for cutting-edge instrument development; computer science and mathematics for exascale computer modeling; data science, machine learning, and artificial intelligence for advanced empirical modeling and making sense of the massive quantities of data collected; meteorology and operations researchers for the next generation of space weather forecasters; community-building skills, including communications, public engagement, and team science, for ambitious citizen science projects; and software engineering for virtually everything.

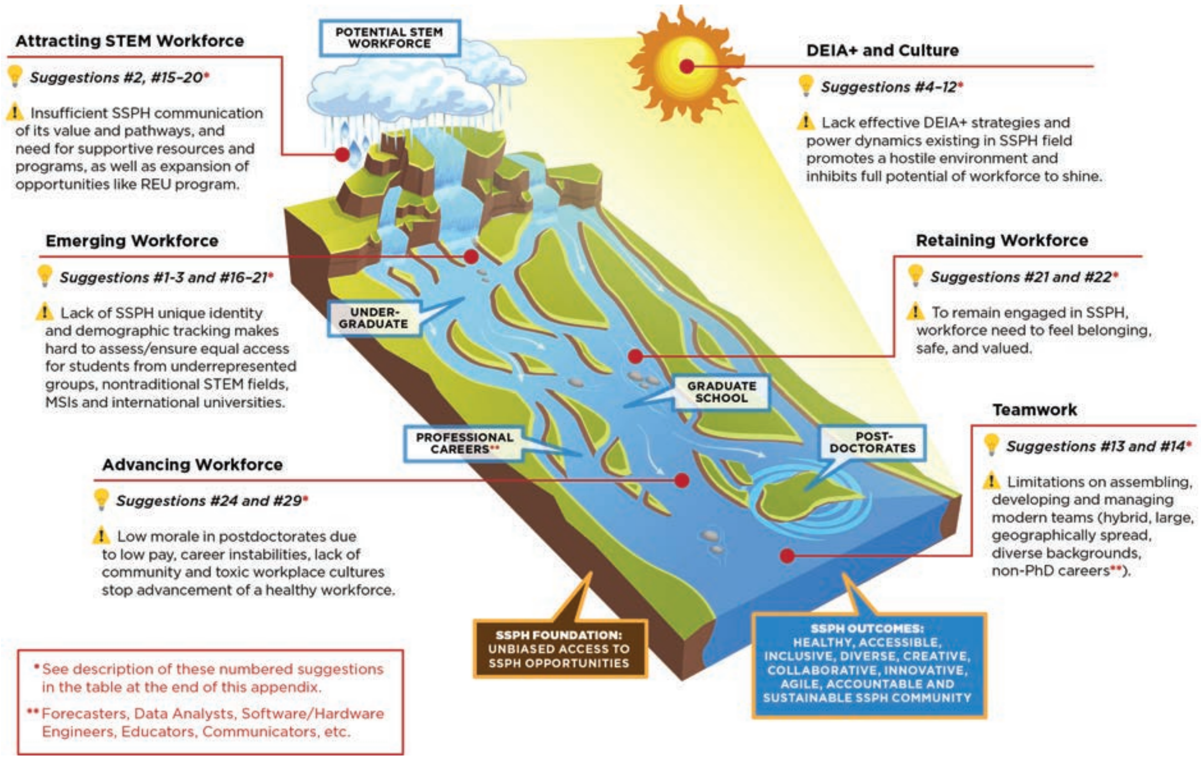

FIGURE F-14 The braided river model of career pathways for a healthy, diverse, and inclusive solar and space physics–heliophysics workforce.
NOTES: The red bullets highlight identified barriers (indicated by the ⚠ symbol) in different moments of the career pathways and the panel's suggested actions (indicated by the 💡 symbol) to overcome them. DEIA+, diversity, equity, inclusion, and accessibility, as well as anti-racism, accountability, and justice; MSI, minority-serving institution; REU, Research Experience for Undergraduates (National Science Foundation); SSPH, solar and space physics–heliophysics; STEM, science, technology, engineering, and mathematics.
SOURCE: Adapted from R.L. Batchelor, H. Ali, K.G. Gardner-Vandy, A.U. Gold, J.A. MacKinnon and P.M. Asher. 2021. "Reimagining STEM Workforce Development as a Braided River." *Eos* 102. https://doi.org/10.1029/2021EO157277. CC BY-NC-ND 3.0.

Currently, the profession of "heliophysicist" is quite limited, primarily referring to those with science and engineering PhDs who pursue career trajectories that lead to either a professorship or research career. This limited view neglects the significant number of pathways that contribute to solar and space physics (heliophysics) education, public outreach and communications, professional development training, operations, infrastructure development, computer modeling, space technology and instrument development, and management. It also neglects the expectations of the emerging workforce that include demands for flexibility around remote work and increased opportunities in broader technology industries and other career paths. Even more broadly, it neglects the rapidly growing commercial space sector. To accommodate the diverse needs of the profession, it is necessary to expand the definition of the solar and space physics (heliophysics) community to include a wider variety of entry points, skill sets, training opportunities, and career trajectories. Many of the existing education programs can contribute to the training of the space scientists and engineers that are needed to support the vast commercial space ecosystem, and companies would benefit from a workforce knowledgeable about the space environment.

F.8.1 Overarching Goal for the Next Decade

The solar and space physics (heliophysics) community expands its definition of community to be able to attract and retain talented students, early career, and other professionals to contribute to addressing solar and space physics (heliophysics) fundamental and applied problems.

F.8.2 Identified Barriers

Recognizing that the traditional rigid pipeline model, with its narrow definition of the community (PhD to researcher or professor) and single-entry point with multiple “leaky” exits, limits efforts to build and support the diverse solar and space physics–heliophysics community. Moving from the pipeline model to the braided stream model would create a healthier and sustainable community by identifying different career paths. It would also enable thinking not only about exit points (barriers) and the traditional main career channel, but also about entry paths and other career paths (such as for those with undergraduate or master’s degrees) that make up the community. For example, as shown in Figure F-14, the braided stream model enables one to envision colleagues at R2 universities,[9] liberal arts colleges, and minority-serving institutions, in addition to the R1 universities[10] with graduate programs in solar and space physics, considering how best to support their careers and programs that support the solar and space physics community.

Attracting, retaining, and advancing diverse talent are important aspects that will define the health and vitality of solar and space physics–heliophysics over the next decade. This is especially so in light of the systemic biases that exist in scholarly research communities, including heliophysics, which lead to a lack of diversity in the field (AGU 2018 and AAS 2018 summarized in Jones and Maute 2022; Liemohn et al. 2023). There now exist a significant number of evidence-based practices for attracting and retaining new and diverse talent both inside and outside of STEM. The community can learn from these evidence-based practices and adapt such practices quickly and effectively over the next decade. A number of these evidenced-based practices are outlined and referenced in a recent National Academies report (NASEM 2020b) that investigated promising practices for addressing the underrepresentation of women in science, engineering, and medicine. A goal over the next decade is to be moving toward expanded recruitment and solidified retention, especially for those in solar and space physics–heliophysics who are from historically minoritized communities in STEM.

- *Attracting:* Traditionally, a slight majority of people in the solar and space physics research community received their undergraduate degrees in physics programs (results from 2013 decadal survey). The others obtained degrees in a wide variety of disciplinary departments, including geoscience, atmospheric sciences, and engineering. About half of the current solar and space physics science research workforce obtained degrees abroad; the other half came mostly from about 12 universities across the country, a fact that highlights the obstacle for graduates from nontraditional and minority-serving institutes to join the field. One of the most effective pathways to the solar and space physics research career has been the NSF REU program. However, there are a variety of other career pathways in solar and space physics (such as in the space weather operations or space technology areas) that are hidden from many students and early career professionals, limiting their possible career transitions and alternatives.
- *Retaining:* To remain engaged in the field, professionals need to feel they belong and are safe and valued. Safety of the community includes safe workplace environments, access to health care, protections for gender identity and sexual orientation, and gun safety. Many states have health care access restrictions, lack of protections for the LGBTQ+ community, and lax gun safety laws.

[9] Classified as those with high research activity.
[10] Classified as those with very high research activity.

- *Advancing and enabling professional growth and success:* Graduate students and postdocs need to be provided a living wage and be well mentored. The postdoc career stage is designed to be a temporary training position that provides significant career and skill growth. Low morale among postdocs due to low pay, career instability, lack of community mentor training and evaluation, and toxic workplace cultures has only been exacerbated since the start of the pandemic. For those who identify as female, people of color, and people from other marginalized communities, there are systemic barriers to equal opportunity to participate, including gender and racial bias in proposal and paper reviews, invited speakers and panelists, and awards (Ford et al. 2018; Graves et al. 2022; Hanson et al. 2020; Lerback et al. 2020; Ranganathan et al. 2021).

F.8.3 Suggestions

As noted above, the panel's suggestions are numbered but not rank ordered, and they are identified as short term (immediate), medium term (by the next midterm assessment), or long term (by the next decadal survey). They are also identified as addressed to attracting, retaining, or advancing diverse talent.

Attracting

15. *The Value of Solar and Space Physics–Heliophysics as a Potential Career Path* (Medium Term). The panel suggests that NASA, NOAA, and NSF create opportunities for the community to clearly develop and articulate the "value" of solar and space physics–heliophysics as a potential career path. A critical aspect to attracting and retaining talent is ensuring a meaningful value proposition to entering the field. "Value" in this context includes doing interesting and personally fulfilling work, but also includes work–life balance, opportunity costs, success rates, career stability, and financial compensation. This definition of value needs to also include the experience of people who contribute to the field, from undergraduates to postdocs, but ultimately pursue opportunities elsewhere. Absent a clear value to pursuing a career in heliophysics, one cannot hope to attract and retain a workforce to make solar and space physics–heliophysics a desirable, thriving, technically competent, and eventually diverse field of study. Clearly articulating and quantifying this "value" is needed.

16. *Multitude of Solar and Space Physics–Heliophysics Career Pathways* (Medium Term). The panel suggests that NASA, NOAA, and NSF support the panel's proposed heliophysics consortium to create a centralized career resource center and advertise the multitude of solar and space physics–heliophysics career pathways. These would include opportunities for those with undergraduate, master's, doctoral, and no degrees, and for those from underrepresented minority groups. The full breadth of the community, including other professionals who are part of large teams (e.g., programmers and communication specialists) and career pathways in solar and space physics–heliophysics, needs to be determined. This includes careers "outside" the research community, such as careers in space weather operations, mission and instrument technology development, and the burgeoning commercial space sector.

17. *Solar and Space Physics–Heliophysics Activities in Curriculum and Degree Programs* (Medium Term). The panel suggests that NASA, NOAA, and NSF fund the development of solar and space physics–heliophysics activities for introductory physics courses, "introductory" solar and space science courses, and relevant curriculum and degree programs. The expertise of midcareer and established NSF FDSS and CAREER [Faculty Early Career Development] Award winners could support the proposed heliophysics consortium to identify and support the higher education community, especially in developing mentoring efforts for early career faculty.

18. *Citizen Science Initiatives* (Short Term). The panel suggests that NSF and NASA continue to support citizen science initiatives. Professional societies (such as AGU, AAS, and AMS), nonprofit STEM partners (such as the Adler Museum's Zooniverse), and the proposed heliophysics consortium can help connect and engage those interested in and involved in citizen science to add pathways in the solar and space physics–heliophysics braided stream (see Figure F-14) and enable science, science communication, and public engagement.

19. *Education and Public Outreach and Workforce Development Opportunities* (Short Term). The panel suggests that NASA and NSF fund the creation and expansion of education and public outreach and workforce development opportunities. These activities span from K–12 through the post-PhD level, focusing on increasing DEIA+ and collaborating with minority-serving institutions and targeting underserved populations, including nontraditional students. The proposed heliophysics consortium could be used to advertise and highlight research and funding opportunities in education and public outreach and connect those engaged in those fields. In addition, the proposed heliophysics consortium could pilot new workforce development opportunities to reach currently marginalized student populations by supporting alternatives to traditional internships, such as virtual research opportunities, as well as recruiting from minority-serving institutions.

20. *Diversify Undergraduate Research Experiences* (Medium Term). The panel suggests that NASA and NSF expand opportunities to support and diversify undergraduate research experiences. This would include the support and development of a network of programs for potential applicants (such as a common app to enable highly qualified and diverse applicants to find a program), professional development opportunities for both students and faculty mentors (including inclusive mentoring training), and data collection to support continued mentoring and understanding of the effects of the programs. The increase in opportunities could be through expansion of solar and space physics–heliophysics REU programs, opportunities for NSF and NASA investigators to request undergraduate research supplements, and programs specifically targeted to fund undergraduate research programs and opportunities (such as the National Center for Atmospheric Research's Significant Opportunities in Atmospheric Research and Science [SOARS]). It could also include expanding the variety of research experiences available to include opportunities for hybrid or virtual research or provide more flexible time frames, such as short (a week or 2) undergraduate experience "camps" instead of the traditional 8- to 12-week REU experiences; such short-term camps would be more accessible and have less environmental impact.

Retaining

21. *Educational and Training Initiatives* (Short Term). The panel suggests that NASA and NSF continue to fund summer schools, student workshops, and other STEM and solar and space physics-heliophysics-related educational and training initiatives; professional and mission-focused training programs (such as early career investigator programs); and mentor training and evaluation. These programs enable the training of a diverse next-generation student and early career cohort in emerging techniques and the evolving needs of the solar and space physics–heliophysics community, including computer programming, data and cloud-based science, and space weather operations.

22. *Physical and Psychological Safety, and Accessibility* (Short Term). The panel suggests that NSF, NOAA, and NASA support the community by considering the full physical and psychological safety and accessibility of all participants in selecting meeting locations. Adopting several leading inclusion practices for conferences, meetings, and workshops will contribute to a healthier and more diverse community. For example, announcements could include a community code of conduct, gender neutral restrooms, family-friendly policies (onsite child care, family grants, and virtual options), and inclusion of pronouns on badges. Despite their shortcomings, remote or hybrid meetings could be incentivized to reduce the environmental travel impact and enhance accessibility for people from minority-serving institutions and the international community (Marabelli et al. 2023).

Advancing

23. *Continual Evaluation for Bias* (Short Term). The panel suggests that NASA, NSF, NOAA, conference organizers, AGU, and solar and space physics institutions begin the continual evaluation for bias of invited speakers and panelists, journal editorial boards, referees, grant reviewers and panelists, advisory boards, and funding and paper acceptance outcomes. This responsibility spans the funding agencies and professional societies and could be coordinated by the panel's proposed heliophysics consortium. Efforts

to minimize bias (such as NASA's dual-anonymous peer review) could be expanded where possible. Opportunities could also be expanded to support early career positions (such as NSF's FDSS program) and create and expand mentoring programs, for both individuals and institutions. The panel also suggests that professional societies (such as AGU) be required to make their editorial, publications, meetings, and award data publicly available.

24. *Learning and Implementing DEIA+ Leading Practices* (Medium Term). The panel suggests that NASA, NOAA, and NSF require all funding calls to include opportunities to support learning and implementing DEIA+ leading practices for individuals, teams, and organizations. NASA provides workshops for developing, implementing, and evaluating DEIA+ plans, and it could include the quality of the DEIA+ plan in the overall evaluation of proposals. NSF could assign a larger weight to the broader impacts effort and use it only as a potential factor in the overall evaluation of a proposal. The panel suggests that agencies support evaluation of different DEIA+ plan efforts and provide these reports and resources to support the broader community.

25. *Assess the Balance Between Different Degrees and Positions* (Medium Term). The panel suggests that NASA, NOAA, and NSF fund the proposed heliophysics consortium to assess the balance between the number of PhDs, postdocs, and permanent positions, as well as the balance between soft money and hard money permanent positions. Sharing the results of these regular assessments would inform those considering solar and space physics–heliophysics career paths and help the community address imbalances.

26. *Promote Work–Life Balance* (Long Term). The panel suggests that NASA, NOAA, and NSF—in their grants, contracts, fellowships, and internships—promote well-being that includes providing a living wage; encouraging family-friendly policies, including child care subsidies; supporting professional development opportunities; and providing seed funding for early career and bridge funding for mid- and experienced career members. Work–life balance in many competitive professional careers in the United States is difficult to maintain, and solar and space physics–heliophysics is not an exception. Evaluation metrics for hiring, promotion, and awards need to be expanded to include inclusive metrics, such as scientific program leadership, contributions to DEIA+, communication, teamwork, and mentoring, following an "inclusive excellence" model.

27. *Incentives to Include Minority-Serving and Other Small Research Institutions* (Medium Term). The panel suggests that the NASA, NOAA, and NSF programs for large research projects (both mission and modeling, like NASA and NSF's DRIVE Science Centers and Heliophysics Theory Modeling Centers) provide incentives to include applicants from minority-serving and other small research institutions, following the example of NASA's Bridge Program.

28. *Reduce the Time Needed to Write and Evaluate Grant Proposals* (Medium Term). The panel suggests that NASA and NSF investigate ways to reduce the time needed to write and evaluate grant proposals. The amount of time required to compete for funding, the opaque funding rates, and the disadvantages inherent in early career opportunities (e.g., many institutions do not allow postdocs to be PIs) has increased over time. There are many mechanisms that can be leveraged to reduce the amount of labor that goes into an individual proposal. One consideration is using such mechanisms as just-in-time budgeting (Jebsen et al. 2022; NIH 2024), in which certain administrative aspects of a proposal are requested later in the application process, creating a Step 0. Similarly, having down-selects between Step 1 and 2 proposals would reduce the total number of full proposals that are written. In addition, grant cycles targeting students, such as NASA FINESST, could be phased with the academic calendar. Currently, the NASA Heliophysics Division decisions occur late in the summer or at the beginning of the academic year, which negatively affects graduate student support.

29. *Increase the Typical Funding Level for Individual Investigator Grants* (Medium Term). The panel suggests that NASA and NSF increase the typical funding level for individual investigator grants to support a sufficient level of effort by the individual investigator or small teams. The level of support of individual investigator PI-type grant funds is no longer sufficient to support significant individual effort, let alone support small teams or students. Total costs for PhD students at many universities now exceed $100,000 per year, and it needs to increase to support larger stipends. Most investigators, including postdocs and early career soft-money scientists, need to have several funded grants to support their full-time effort, fragmenting their attention to specific problems and contributing to career instability and poor working conditions. The panel recognizes that without increased overall funding, implementing this suggestion would mean a decrease in the number of investigations that can be funded.

F.9 SUMMARY AND PANEL PRIORITIES AND ALIGNMENT WITH RECENT NATIONAL ACADEMIES REPORTS

The panel's suggestions on developing a people-centered, healthy, and sustainable solar and space physics (heliophysics) workforce focuses on DEIA+, culture, teams, and the workforce. The panel envisions a healthy and thriving community that makes significant discoveries and benefits the space-age technological society as a result of its creative, diverse, and inclusive community, as well as with health-promoting and inclusive excellence values. Recognizing that individuals make up all of the components of the solar and space physics (heliophysics) community system leads us to highlight the diversity of experiences and requires diverse approaches to support equity in opportunities. Rodriguez (2016) defines equity as enactment of specific policies and practices that ensure equitable access and opportunities to success for everyone. To be equitable, one cannot treat everyone the same, but one treats individuals according to their needs and provides multiple opportunities for success. Equity can be viewed as providing resources and structures that are not equal but meet people where they are at, to ensure that all people can participate in solar and space physics (heliophysics) (Pendergrass et al. 2019).

The panel considered well-known and documented barriers of race, ethnicity, gender, class, ableism, and background, and hostile workplace climates (Marín-Spiotta et al. 2020); implicit bias in recommendation letters (Houser and Lemmons 2018); disproportionate service expectations (O'Meara et al. 2017a,b); gender, racial, and sexual harassment (Aycock et al. 2019; Clancy et al. 2017); systemic racial disparities in proposal funding (Chen et al. 2022); lower publication acceptance and citation rates (Lerback et al. 2020); fewer speaking opportunities at conferences (Ford et al. 2018, 2019); and many other impediments, such as retaliation for those that choose to support students and colleagues from groups affected by these barriers (Hughes 2018). These barriers impede people from underrepresented groups and gender diverse people, as well as people with disabilities. They are not novel, revelatory, or unfounded through all of STEM.

The panel acknowledges that federal funding agencies (NASA, NOAA, and NSF) and professional societies (AAS, AGU, and AMS) are making slow progress addressing such barriers. Nonetheless, the panel chose to prioritize 13 of the suggestions discussed above on ways to lower barriers in the solar and space physics profession (see Table F-2).

Previous National Academies reports, including the midterm assessment in solar and space physics, the decadal surveys of planetary science and astrobiology and astronomy and astrophysics, the *Advancing Diversity* report, and a number of others have all outlined the barriers to DEIA+ throughout science (see Bagenal 2023). The panel agrees and supports these previous suggestions and recommendations (see a list of relevant recommendations from previous decadal surveys and other relevant National Academies' reports in Annex F.A).

As background for the panel's suggestions, the next section of this appendix presents the findings from the community input papers that the panel received. The subsequent section lists the panel's 29 suggestions and links them to previous recommendations from National Academies' report, which are detailed in the annex to this appendix.

F.9.1 Findings from the Community Input Papers

Table F-1 presents nine themes and summaries of the content from community input papers received by the panel for this decadal survey.

F.9.2 Panel Suggestions

Table F-2 summarizes the panel's 29 suggestions, mapping each one of them to the similar recommendations from recent reports (see Annex F.A) and associated themes from the community input papers, detailed in Table F-1. The panel's 13 high-impact and actionable suggestions are indicated by asterisks and are further elaborated in Box F-1.

Box F-1 details the high-priority suggestions, whether they are for the short term (immediately) or medium term (by the next midterm assessment), and indicates who is responsible for implementation.

TABLE F-1 Summary of Nine Themes from Community Input Papers Received for This Decadal Survey

Themes	Summary
I. DEIA+, Workforce Well-Being, and Culture	These papers focus on diversity, equity, inclusivity, and accessibility (DEIA+), and the invested interest in the solar and space physics community to support DEIA+, mentorship, and efforts to create a healthy working environment.
II. Citizen Science and Crowdsourcing	These papers make recommendations to support citizen science. Furthermore, many of these papers discuss the benefits of citizen science as it pertains to improved science accessibility, education, and cross-disciplinary research.
III. Data Accessibility and Management	These focus on developing more efficient ways in which to collect and disseminate data. These also relate to transdisciplinary efforts.
IV. Funding Infrastructure Changes	Many of the papers make funding recommendations (e.g., supporting citizen science efforts). These papers focus more on changing the infrastructure in which funding is allocated, rather than stating where it be allocated.
V. Open Science, Collaborations, Cross-Disciplinary and Transdisciplinary Support, and Multiscale/System-of-Systems	These papers address examining a bigger scientific scope and pooling in talents from outside of one's "silo" of funding.
VI. Instrumentation	These papers focus on facilities and technological advancements. They also generate training and workforce development opportunities.
VII. Science Training and Workshops	These papers highlight the importance of community summer schools, as well as specialized/focused training workshops to support both education and networking.
VIII. Computational Modeling and Simulation, and Software	These papers discuss the need for multi- and cross-disciplinary skills in order to generate software and models that address fundamental science.
IX. Communication and Public Engagement	These papers address how solar and space physics–heliophysics can be branded and advertised in such a way the public understands and is excited to participate. They also give examples and suggestions for engaging with taxpayers and the world at large.

TABLE F-2 Panel Suggestions Mapped to National Academies Report Recommendations

Number	Suggestion	Themes Addressed in Community Input Papers	Similar Recommendations (Rec) from Recent Reports
1*	A Common Name for the Field	IX	NRC (2014), Rec1.0
2*	Heliophysics Consortium	V	NRC (2014), Rec1.0; NASEM (2020a), Rec3.1; NASEM (2022c), Rec4a; NASEM (2023a), Rec3.1
3*	Demographics Data System	I	NASEM (2020a), Rec5.1, Rec6.1, Rec6.2; NASEM (2022b), Rec7 to Rec9; NASEM (2022c), Rec1; NASEM (2023a), Rec3.1, Rec6.1; NASEM (2023b), Rec6
4*	Committees with DEIA+ Subject-Matter Experts	I	NASEM (2022b), Rec1 to Rec4, Rec9; NASEM (2022c), Rec2; NASEM (2023a), Rec2.1, Rec4.1, Rec6.2
5	DEIA+ Plans for Large Team Proposals	I	NASEM (2020a), Rec3.2.5; NASEM (2022b), Rec5; NASEM (2023b), Rec7
6	Educating the Solar and Space Physics-Heliophysics Community on DEIA+'s Importance	I, VII	NASEM (2022b), Rec10 to Rec12; NASEM (2023a), Rec5.1 to Rec5.5; NASEM (2023b), Rec1, Rec2
7	Policy Changes that Enable Accountability for DEIA+ Efforts	I, IV	NASEM (2022b), Rec6; NASEM (2022c), Rec4a
8*	Core Values of Health Promotion	I	NASEM (2022b), Rec6, Rec15; NASEM (2023), Rec2.1
9*	Mechanisms of Accountability of PIs		NASEM (2023), Rec8.1
10	Ombudsperson to Receive Anonymous Complaints	V	NASEM (2022c), Rec4b; NASEM (2023b), Rec5
11	Mechanisms to Address Unequal Power Dynamics	IV	NASEM (2022c), Rec3a; NASEM (2023a), Rec7.1, Rec8.1, Rec8.3
12*	Support and Reward Those Who Lead Community Efforts	IV	Rec1; NASEM (2022b), Rec13 to 15; NASEM (2022c), Rec3a; NASEM (2023a), Rec8.2; NASEM (2023b)
13*	Science Team Plans for Mission, Center, and Large Investigations	I, IV, V	NRC (2015), Rec8
14	Development of Team Science Activities and Curriculum	I, V, VII, IX	NRC (2015), Rec8
15	"Value" of Solar and Space Physics–Heliophysics as a Potential Career Path	V, VII, IX	
16	Multitude of Solar and Space Physics–Heliophysics Career Pathways	V, VII, IX	NASEM (2020a), Rec3.2.4; NASEM (2023a), Rec3
17*	Solar and Space Physics–Heliophysics Activities in Curriculum and Degree Programs	V, VII	
18*	Citizen Science Initiatives	II	
19	Education and Public Outreach and Workforce Development Opportunities	V, IX	
20*	Diversify Undergraduate Research Experiences	III, VII, VIII	
21	Educational and Training Initiatives	VII	NASEM (2022c), Rec3d
22*	Physical and Psychological Safety, and Accessibility	I, V	NASEM (2022c), Rec4a; NASEM (2023a), Rec 8, Rec11
23	Continual Evaluation for Bias	I, VII	NASEM (2023a), Rec8.1

continued

TABLE F-2 Continued

Number	Suggestion	Themes Addressed in Community Input Papers	Similar Recommendations (Rec) from Recent Reports
24*	Learning and Implementing DEIA+ Leading Practices	I, V	NASEM (2022b), Rec4; NASEM (2023a), Rec6.2
25	Assess the Balance Between Different Degrees and Positions	IV	NASEM (2020a), Rec3.2.5
26	Promote Work-Life Balance	I, IV	NASEM (2022b), Rec13
27	Incentives to Include MSI and Other Small Research Institutions	I, IV, V	NASEM (2022c), Rec3b, Rec3c
28	Reduce the Time Needed to Write and Evaluate Grant Proposals	IV	
29	Increase the Typical Funding Level for Individual Investigator Grants	IV	

NOTES: * indicates high-impact suggestions; see text for discussion. Recommendation numbers were assigned if unnumbered in the original source. DEIA+, diversity, equity, inclusion, and accessibility, as well as anti-racism, accountability, and justice; MSI, minority-serving institution; PI, principal investigator.

BOX F-1
High-Impact and Actionable Suggestions

1. *A Common Name for the Field* (Medium Term). The panel suggests that the community—including the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the National Oceanic and Atmospheric Administration (NOAA), and the higher education community—coalesce around a single name (solar and space physics or heliophysics) so that numbers of faculty, researchers, practitioners, and students can be tracked across departments, institutions, professional societies, and employers. Using keywords in ORCID by individual investigators could over time help self-identify the community, especially as having an ORCID number is now required by professional societies and funding agencies.

2. *Heliophysics Consortium* (Medium Term). The panel suggests an interagency mechanism, funded by NASA, NOAA, and NSF, to unify the multiple subgroups and facilitate networking, collaboration, and communication among them, focusing on integrating and strengthening solar and space physics–heliophysics research that supports the large research intensive universities and laboratories, but also smaller regional universities, minority serving institutions (MSIs), and early career researchers to enable tackling grand challenge solar and space physics–heliophysics questions.

3. *Demographics Data System* (Medium Term). The panel suggests that the relevant agencies systematically and transparently monitor and analyze demographic data on the barriers and opportunities for career advancements, including the continuation of NASA's assessment of gender differences in award rates. The panel suggests that NASA, NSF, and NOAA work with independent organizations (such as the American Institute of Physics) through the proposed heliophysics consortium to conduct regular, 5-year surveys of the community and its culture and routinely provide proposal and award data to the proposed heliophysics consortium. Similarly, the panel suggests that professional societies (the American Geophysical Union [AGU], the American Astronomical Society, and the American Meteorological Society) provide data on meeting attendees and journal authors and referees to the proposed heliophysics consortium. In the panel's conception, the proposed consortium would take the lead in developing, implementing, analyzing, and communicating the results of surveys and the health and vitality of the discipline; it could also engage with social scientists in crafting the surveys, interpreting the results, and recommending actions.

BOX F-1 Continued

4. *Committees with DEIA+ Subject-Matter Experts* (Short Term). The panel suggests that NASA, NOAA, and NSF, as well as other solar and space physics–heliophysics institutions, continue to hire and fund DEIA+ (diversity, equity, inclusion, and accessibility, as well as anti-racism, accountability, and justice) subject matter experts to integrate relevant teams, organizations, and committees to (1) map structural, organizational, individual bias, inequalities, and racism in solar and space physics–heliophysics activities; (2) understand the role of leadership and organization in propagating the issues; (3) create road maps and metrics to improve DEIA+ in heliophysics; and (4) evaluate gatekeepers' and organization's programs, policies, and practices in an effective way (e.g., using the National Institutes of Health as an exemplar).

8. *Core Value of Health Promotion* (Medium Term). The panel suggests that salaries and stipends at the undergraduate and graduate levels be raised to a livable wage adjusted for location and reviewed annually as part of ensuring that solar and space physics–heliophysics community institutions and funding agencies have health-promotion at the center of their mission. The Okanagan Charter adopted by many research universities is a model (International Conference on Health Promoting Universities & Colleges, 2015). NASA and NSF can support the well-being of the solar and space physics–heliophysics community by increasing the undergraduate and graduate student stipend and postdoc salary minimum requirements to a livable wage adjusted by location (e.g., locality-adjusted general schedule pay). Levels at or above these minimums would be a requirement for programs such as NSF's Research Experiences for Undergraduates (REUs), NASA's Future Investigators in NASA Earth and Space Science and Technology (FINESST) program, and postdoctoral fellowships from NSF's Division of Atmospheric and Geospace Sciences, and individual investigator grants funded through programs such as NSF's Geospace Environment Modeling (GEM) and NASA's Research Opportunities in Space and Earth Science (ROSES) programs.

9. *Mechanisms of Accountability of Principal Investigators* (Medium Term). The panel suggests that NASA, NSF, NOAA, and other relevant institutions adopt a code of research ethics and conduct (modeled after that of the AGU or other agencies) for individual laboratories and teams. In addition, the panel suggests that policies be developed that prevent principal investigators who have had disciplinary findings of research misconduct from taking grants with them to new institutions (i.e., the "pass the abuser" issue).

12. *Support and Reward Those Who Lead Community Efforts* (Medium Term). The panel suggests following Goal 2, Suggestion 4 of the decadal survey in astronomy and astrophysics (NASEM 2023b) that federal agencies provide material support to researchers who build and lead programs designed to retain, recruit, and advance people from underrepresented minority communities in heliophysics. This approach would expand the community's definition of "excellence" to "inclusive excellence" by recognizing and rewarding the value added for these efforts. An example highlighted in Astro2020 would be to increase budget size for research grants for those who propose to advance DEIA+ efforts in their institution or the broader community. Funding 5–10 grants with an additional $100,000 would cost between $500,000 to $1 million per year per agency.

13. *Science Team Plans for Mission, Center, and Large Investigations* (Medium Term). The panel suggests that NASA and NSF provide sufficient resources to develop science team plans (e.g., charters) and make them required for proposals as an evaluated factor in order to strengthen solar and space physics–heliophysics investigations. Review panels would include team experts or trained reviewers, as was done for the NASA Drive Center evaluation. Agencies would offer team science plan resources prepared by team experts and pay attention to the level of effort of each member of the team (thinking of efficiency and career impact), how well early career scholars are mentored and trained, and the quality of a succession plan.

continued

BOX F-1 Continued

17. *Solar and Space Physics–Heliophysics Activities in Curriculum and Degree Programs* (Medium Term). The panel notes that the expertise of midcareer and established NSF Faculty Development in the Space Sciences and CAREER (Faculty Early Career Development) Award winners could support the proposed heliophysics consortium in identifying and supporting the higher education community, especially in developing mentoring efforts for early career faculty.

18. *Citizen Science Initiatives* (Short Term). The panel suggests that NSF and NASA call on professional societies (such as AGU), nonprofit STEM (science, technology, engineering, and mathematics) partners (such as Adler Museum's Zooniverse) and the proposed heliophysics consortium to help connect and engage those interested in and involved in citizen science to add pathways into the solar and space physics–heliophysics community and promote science, science communication, and public engagement.

20. *Diversify Undergraduate Research Experiences* (Short Term). The panel suggests that NASA and NSF support and develop a network of programs to exchange applicants (e.g., a common app to enable highly qualified and diverse applicants to find a program), professional development opportunities for both students and faculty mentors (including inclusive mentoring training), and data collection to support continued mentoring and understanding of the impact of the programs. The increase in opportunities could be through expansion of solar and space physics–heliophysics REU programs, opportunities for NSF and NASA investigators to request undergraduate research supplements, and programs specifically targeted to fund undergraduate research programs and opportunities (e.g., programs such as SOARS [Significant Opportunities in Atmospheric Research and Science]). The panel also suggests that NASA and NSF expand the variety of research experiences available to include opportunities for hybrid or virtual research or provide more flexible time frames, such as short (1–2 weeks) undergrad experiences "camps" instead of the traditional 8- to 12-week REU experiences; such short experiences would be more accessible and have less environmental impact.

22. *Physical and Psychological Safety and Accessibility* (Short Term). The panel suggests that NSF, NASA, and NOAA adopt a number of leading practices for inclusion for conferences, meetings, and workshops that will contribute to a healthier and more diverse solar and space physics–heliophysics community. Examples include a community code of conduct; gender-neutral restrooms; family-friendly policies, such as onsite child care, family grants, and virtual options; and inclusion of pronouns on badges. Remote or hybrid meetings could be incentivized to reduce the environmental travel impact and enhance accessibility for people from MSIs and for the international community.

24. *Learning and Implementing DEIA+ Leading Practices* (Medium Term). The panel suggests that NASA provide workshops for developing, implementing, and evaluating DEIA+ plans and include the quality of the DEIA+ plan in the overall evaluation of the proposal. The panel suggests that NSF assign a larger weight to the broader impacts effort and not use it only as a potential factor in the overall evaluation of a proposal. The panel suggests that both agencies support evaluation of different DEIA+ plan efforts and provide these reports and resources to support the entire solar and space physics–heliophysics community.

F.10 REFERENCES

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F.11 GLOSSARY

Accessibility: "Accessible" means a person with a disability is afforded the opportunity to acquire the same information, engage in the same interactions, and enjoy the same services as a person without a disability in an equally effective and equally integrated manner, with substantially equivalent ease of use. (From Department of Education)

Anti-Racism: The practice of actively identifying and opposing racism. The goal of anti-racism is to actively change policies, behaviors, and beliefs that perpetuate racist ideas and actions. (From Boston University)

Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR): A National Science Foundation sponsored initiative to understand the fundamental properties of the space-atmosphere interaction region, to identify the interconnected processes that define the local and global behavior, the evolution, and influence on the Sun-Earth system; and to explore the ionosphere-thermosphere predictability.

Culture: The values and beliefs, language, communication, and practices that are shared in common by a group of people.

Diversity: The practice or state of involvement of persons across a variety of social and demographic characteristics within organizational, institutional, and interactional settings. (From Advancing DEIA in the Leadership of Competed Space Missions [NASEM 2022b])

Diversity, Equity, Inclusion, Accessibility plus (DEIA+): The phrase used to define policies, behaviors and beliefs that support the opportunity for all to participate and develop within a community. The "+" includes anti-racism, accountability, and justice.

Equity: The absence of barriers, biases, and obstacles that impede access, fair treatment, and opportunity for contribution by all members of a community, recognizing that different resources or approaches are needed to remedy the uneven playing field that exists across different groups. (From Advancing DEIA in the Leadership of Competed Space Missions [NASEM 2022b])

Geospace Environment Modeling (GEM): A National Science Foundation sponsored initiative to coordinate and focus research on the near-earth portion of geospace from the lower ionosphere to where the Earth system interacts with the solar wind.

Historically minoritized communities in STEM: Socio-demographic groups (e.g., certain genders, racial/ethnic groups) that, as a result of historical and contemporary processes of oppression and bias have been excluded from full and representative participation in STEM. (From Advancing DEIA in the Leadership of Competed Space Missions [NASEM 2022b])

Inclusion: The practice of facilitating the equal distribution of opportunities, resources, and recognition to persons regardless of social and demographic characteristics within organizational, institutional, and/or interactional environments. (From Advancing DEIA in the Leadership of Competed Space Missions [NASEM 2022b])

Minority Serving Institution (MSI): Institutions of higher education that serve minority populations and include Historically Black Colleges and Universities (HBCUs), Hispanic Serving Institutions (HSIs), Tribal Colleges and Universities (TCUs), and Asian American and Pacific Islander Serving Institutions (AAPISIs).

Solar, Heliospheric, and INterplanetary Environment (SHINE): A National Science Foundation sponsored initiative within the solar, interplanetary, and heliospheric communities, dedicated to promoting an enhanced understanding of the processes by which energy in the form of magnetic fields and particles are produced by the Sun and/or accelerated in interplanetary space and on the mechanisms by which these fields and particles are transported to Earth through the inner heliosphere.

Underrepresented Minority (URM): The federal government classifies African American, Hispanic, Native American, Alaskan and Pacific Islander, women, and those with disabilities URM with respect to STEM. Note that this group does not include Asian Americans, who are slightly over-represented in STEM compared to their overall percentage of the U.S. population. If you include Asian-Americans, this category accounts for about 69 percent of the U.S. population (NCSES 2023) (i.e., White-Males make up about 31 percent of the U.S. population).

Well-Being: A positive outcome that is meaningful for people and society, because it tells us that people perceive that their lives are going well and integrates mental health (mind) and physical health (body). Good living conditions (for example, affordable housing) and other positive quality of life indicators (job satisfaction) are essential for well-being.

ANNEX F.A

RELEVANT RECOMMENDATIONS FROM PREVIOUS DECADAL SURVEYS AND OTHER NATIONAL ACADEMIES REPORTS

New Executive Order on Racial Equity

Expanding on the executive order on DEIA issued on the President's first day in office, on February 16, 2023, the Biden administration issued a new executive order on racial equity and supporting underserved communities. The new order "reaffirms the Administration's commitment to deliver equity and build an America in which all can participate, prosper, and reach their full potential" (Biden 2023b).

Among its provisions:

- Gives federal agencies 30 days to set up Agency Equity Teams and designate senior leaders to implement the mandate. Agency Equity Teams will be responsible for equity training and leadership. It is also designed to improve collaboration and accountability and streamline progress reporting.
- Agencies produce yearly equity action plans.
- Promotes transparency and equity with data. The order directs the Interagency Working Group on Equitable Data (now institutionalized at the National Science and Technology Council) to improve data collection and analysis to better report progress on racial equity initiatives.
- Requires agencies to improve their community engagement process and to consult with communities as equity action plans are developed.

"Achieving racial equity and support for underserved communities is not a one-time project. It must be a multi-generational commitment, and it must remain the responsibility of agencies across the Federal Government," President Biden said in the executive order (Biden 2023a). The solar and space physics–heliophysics community needs to work with NASA, NOAA, and NSF to be engaged in these efforts.

Identifying Key Recommendations from Previous Reports

Extracts from the relevant recommendations in recent National Academies reports are shown in Table F.A-1.

TABLE F.A-1 Relevant Recommendations from Recent National Academies Reports

Report and Recommendation Number	Recommendation Text
Solar and Space Physics: A Science for a Technological Society (NRC 2013)	
NRC (2013) Rec1.0	Implement DRIVE (Diversify, Realize, Integrate, Venture, Educate)): Educate: 1. The NSF Faculty Development in the Space Sciences (FDSS) program should be continued and be considered open to applications from 4-year as well as Ph.D.-granting institutions as a means to broaden and diversify the field. NSF should also support a curriculum development program to complement the FDSS program and to support its faculty; 2. A suitable replacement for the NSF Center for Integrated Space Weather Modeling summer school should be competitively selected, and NSF should enable opportunities for focused community workshops that directly address professional development skills for graduate students; 3. To further enhance the visibility of the field, NSF should recognize solar and space physics as a specifically named subdiscipline of physics and astronomy by adding it to the list of dissertation research areas in NSF's annual Survey of Earned Doctorates.
Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics: A Midterm Assessment (NASEM 2020)	
NASEM (2020) Rec3.1	NASA and NSF should continue to use the DRIVE framework within their Research and Analysis programs. As the program elements that are part of DRIVE continue to evolve, they should remain visible and continue to be tracked in a transparent manner.
NASEM (2020) Rec3.2.4	NASA and NSF should maximize the scientific return from large and complex data sets by supporting (1) training opportunities on modern statistical and computational techniques; (2) science platforms to store, retrieve, and process data using common standards; (3) funding opportunities for interdisciplinary collaboration; and (4) supporting the development of open-source software. These four components should be considered alongside experimental hardware in the planning and budgeting of instrumentation.
NASEM (2020) Rec3.2.5	NASA should find ways to increase solar and space physics community participation in strategic missions and enhance the diversity of mission teams. The Planetary Science Division's Participating Scientist program is a model that could be considered to achieve this goal.

continued

TABLE F.A-1 Continued

Report and Recommendation Number	Recommendation Text
NASEM (2020) Rec5.1	NASA, NSF, and NOAA should develop strategic plans for the Heliophysics community with goals and metrics to improve the diversity of race, gender, age, and country of origin. The next decadal survey should include a State of the Profession Panel, similar to the Astro2020 decadal survey. The State of the Profession Panel should have in advance the demographics/diversity survey data recommended in this report's Recommendation 6.2.
NASEM (2020) Rec6.1	NASA and NSF should implement and fund advanced planning for the next solar and space physics decadal survey that involves the community strategically in the formulation of decadal goals and stretch goals (ambitious objectives that might extend past the next decade). NASA and NSF could request the Space Studies Board's Committee on Solar and Space Physics (SSB-CSSP) to evaluate options for implementing this planning for the next decadal survey.
NASEM (2020) Rec6.2	NASA Heliophysics Division should conduct a demographics/diversity survey before the next heliophysics decadal survey to understand how the community's demographics have evolved and to assess whether progress has occurred in enhancing diversity in the community (see also this report's Recommendation 5.1). Thereafter, to benefit all of the space science disciplines within NASA's Science Mission Directorate (SMD) and to inform decadal survey planning across SMD, NASA, at the SMD-level, should conduct this demographics/diversity survey on a 5-year cadence with clear identification of science areas relevant for each science division. It is important that career survey specialists, such as the American Institute of Physics, are involved in a new survey.
Advancing Diversity, Equity, Inclusion, and Accessibility in the Leadership of Competed Space Missions (NASEM 2022a)	
NASEM (2022a) Rec1	NASA should empanel an ongoing NASA Advisory Council (NAC) committee specifically focused on diversity, equity, inclusion, and accessibility (DEIA), whose committee chair serves directly on the NAC. This committee should have a broad charter and external world-class membership in this area to directly advise top NASA leadership and ensure an ongoing strong focus on NASA's broadening DEIA efforts.
NASEM (2022a) Rec2	NASA should work to make the pre-proposal "competition before the competition" process transparent and accessible. Additionally, NASA should use its own resources to expand support of pre-proposal and proposal efforts of diverse, external principal investigators through its field centers and encourage other institutions in the business of supporting and investing in Science Mission Directorate proposals and missions to do the same.
NASEM (2022a) Rec3	NASA should reconsider the requirements for site visits to emphasize the evaluation of technical and programmatic readiness, and eliminate any unnecessary elements. NASA should evaluate the benefit of providing uniform funding to each team that is preparing a site visit, disallowing supplemental funding and other contributions that may result in inequities across teams.
NASEM (2022a) Rec4	NASA Science Mission Directorate (SMD) should develop and make public a systematic and transparent process to assess how the review of proposals submitted for research support is conducted. • Moreover, NASA SMD should collaborate with experts to develop and employ an assessment of its mission proposal review process as well as involve experts on disparities in research funding experienced by historically marginalized groups. Such an assessment should also include gathering feedback from proposers. • In the longer term, NASA Headquarters should develop a comprehensive assessment of its proposal review processes, not only with the principal investigator–led missions, but to be employed agencywide. • This analysis and assessment should include consideration of emergent bias-reducing practices (such as Dual-Anonymous Peer Review) and methods to track, identify, and reduce bias in the review and evaluation process.

TABLE F.A-1 Continued

Report and Recommendation Number	Recommendation Text
NASEM (2022a) Rec5	In keeping step with its core values of diversity, equity, inclusion, and accessibility (DEIA), NASA Science Mission Directorate should: • Require announcements of opportunity to include a description of how the dimensions of DEIA, including talent development and workforce diversity, are critical to NASA, and require proposals to include a plan for DEIA in the proposed missions describing how the proposed DEIA activities are key for mission success. • Establish a separate, scorable evaluation criterion of the proposed DEIA plans as part of mission proposal review and provide training for reviewers to better equip them to appropriately evaluate proposals concerning DEIA dimensions. • Engage with DEIA experts to implement the new requirements for mission proposals in ways that advance the overarching goal of broadening participation of underrepresented groups in missions. • Establish monitoring and assessment processes to continually measure the impact of the new DEIA plan requirement on progress toward NASA's stated DEIA goals.
NASEM (2022a) Rec6	NASA should regularly monitor and assess adherence to the proposed diversity, equity, inclusion, and accessibility plans throughout the mission lifecycle and require up-to-date reporting on climate within mission teams in ways that go beyond compliance. For designing and interpreting climate assessments, NASA Science Mission Directorate should engage with content experts (e.g., survey design experts, social science scholars).
NASEM (2022a) Rec7	NASA Headquarters (HQ) should develop a systematic and transparent process that employs routine monitoring and tracking of proposal submissions and selections, and submit an annual report of these data to the diversity, equity, inclusion, and accessibility committee of the NASA Advisory Council as well as make the report publicly available. This report should include data on dimensions such as funding rates and diversity in team participation in principal investigator–led missions as well as research and analysis grants; but could also include data on other important dimensions of interest to the agency. NASA HQ should seek professional statistical expertise to set in place the needed infrastructure to support robust data collection, monitoring, and reporting including, but not limited to, adequate staffing, data collection standards of practice, monitoring and analytic systems, annual reporting capability, and external partnerships, to overcome the challenges of tracking participation in NASA's Earth and space science activities.
NASEM (2022a) Rec8	Working with experts in demographics data gathering and analysis, NASA should review, update and expand the NSPIRES Personal Profile questions and regularly encourage proposers to update their responses.
NASEM (2022a) Rec9	To regularly assess the state of the profession, NASA Science Mission Directorate should provide funding for professional organizations (e.g., American Institute of Physics, American Astronomical Society, American Geophysical Union, American Physical Society, etc.) to employ the necessary professional expertise in survey methodology and statistical analysis to systematically carry out surveys of the workforce, within and across the four science divisions with competed missions, to inform NASA of the participation of different demographic groups as well as the barriers and opportunities for advancement along entire career pathways in the Earth and space sciences.
NASEM (2022a) Rec10	NASA should expand and increase the frequency of training programs that are aimed at encouraging women and historically minoritized communities to become more involved in mission leadership.
NASEM (2022a) Rec11	To engage and train diverse teams at all stages of professional talent development, NASA should offer mission-related research, mentorship, and training opportunities—ideally, integrated into actual NASA missions—through colleges/universities as well as NASA centers, that should start as early as first-year undergraduates and graduate students (e.g., internships), and extend to the ranks of postdocs (e.g., fellowships), and established scientists (e.g., participating scientists).

continued

TABLE F.A-1 Continued

Report and Recommendation Number	Recommendation Text
NASEM (2022a) Rec12	Principal investigator (PI)-led missions present opportunities for aspiring PIs to gain invaluable experiences. NASA should expand resources (e.g., instructional materials, seminars, workshops) for aspiring PIs to gain leadership experience and connect with individuals with mission experience for mentorship opportunities. This may include: • Integrating aspiring PIs as mentees in roles on mission teams, including the higher leadership positions. This could be achieved by including developmental positions in all missions (i.e., competed, non-competed, and instrument investigations), which may require increasing the PI-managed costs. • Encouraging aspiring PIs to pursue entry points to mission leadership, such as proposing to smaller, low-cost mission opportunities, (e.g., suborbital, SmallSats and CubeSats, instrument development, and hosted payloads). • Expanding structured networking opportunities at relevant disciplinary conferences such as meet-and-greets where aspiring PIs can connect with collaborators and meet existing PIs, and participate in presentations and question and answer sessions led by NASA personnel about the proposal process.
NASEM (2022a) Rec13	NASA should evaluate the skills and expertise needed for success as a principal investigator (PI) beyond scientific competencies, including abilities leading and managing diverse, equitable, inclusive, and accessible teams. This more expansive set of competencies should be reflected in discussions about PI-ship in instructional materials and other outreach efforts.
NASEM (2022a) Rec14	In order to ensure a vibrant, next generation pool of excellent and diverse talent for leadership in competed space missions, NASA Science Mission Directorate, in collaboration with the Office of STEM Engagement, should provide consistent and adequate funding for science, technology, engineering, and mathematics initiatives that are explicitly centered on diversity, equity, inclusion, and accessibility, address recruitment and retention challenges in the Earth and space sciences, and support and expand opportunities for individuals from underrepresented groups. These investments should reflect a pathways approach spanning the academic and career continuum from post-secondary through post-PhD years in order to establish flexible and robust education-to-career trajectories into the Earth and space sciences workforce, and ultimately into principal investigator–led missions. A systematic process should also be in place to document measurable impacts of these investments.
NASEM (2022a) Rec15	Recognizing the critical role that Historically Black Colleges and Universities (HBCUs), Hispanic-Serving Institutions (HSIs), and other Minority Serving Institutions (MSIs) play in educating and employing women and racially minoritized populations in the Earth and space sciences workforce, NASA leadership, specifically the Science Mission Directorate (SMD) and the Office of STEM Engagement Associate Administrators, should charter a joint team to examine and strengthen the historic and current relationship between the two organizations with respect to investments in MSIs. NASA's investments should also redress the historical inequities in NASA supported research and training at these institutions. Specifically, NASA should: • Reinvest in talent development programs in partnership with MSIs specifically related to NASA missions, such as the undergraduate-to-graduate "bridge" type programs previously supported by NASA SMD's Minority University and College Education and Research Partnership Initiative program. • Further leverage NASA programmatic assets such as Minority University Research and Education Programs (MUREP), MUREP Institutional Research Opportunity, and Science Activation to advance broad access to all of its missions, and further enhance early preparation and research engagement of students and early-career researchers, including underrepresented communities. • Provide funding to support mission-related work and activities (e.g., building and designing instruments for spaceflight, hosting science team meetings, etc.) as a means of enhancing research capacity at HBCUs, HSIs, and other MSIs.

TABLE F.A-1 Continued

Report and Recommendation Number	Recommendation Text
Advancing Antiracism, DEI in STEMM Organizations (NASEM 2023a)	
NASEM (2023a) Rec2.1	Federal funding agencies, private philanthropies, and other grantmaking organizations should provide increased opportunities for grants, awards, and other forms of support to increase understanding of how the policies, programs, and practices of Historically Black Colleges and Universities (HBCUs) and Tribal Colleges and Universities (TCUs) support students and faculty. Notably, one issue for further investigation should be understanding the core principles of historically-based minority serving institution (MSI)-based programs and how to translate them to predominantly White institutions of higher education and other science, technology, engineering, mathematics, and medicine organizations. In addition, predominately white institutions should seek sustainable partnerships with all MSIs (HBCUs, TCUs, Hispanic Serving Institutions, and Asian American, Native American, and Pacific Islander Serving Institutions).
NASEM (2023a) Rec3.1	To understand the relative persistence of students in science, technology, engineering, and mathematics (STEM) higher education, data collection organizations, such as the National Center for Science and Engineering Statistics and the National Center for Education Statistics, should collect and share online with the public information on the demographics of students entering college planning to study STEM and their subsequent educational outcomes, disaggregated by race and ethnicity, gender, and field of study, including: • How many complete a STEM degree, • How many switch to and complete a non-STEM degree, and • How many leave college without a degree.
NASEM (2023a) Rec4.1	There are a few noteworthy ways to describe how people from historically and systemically minoritized groups respond to racism in science, technology, engineering, mathematics, and medicine (STEMM) educational and professional environments. These responses can be loosely grouped as follows: exiting the field, implementing strategies to fit in, and collectively mobilizing to transform the STEMM environment.
NASEM (2023a) Rec5.1	Leaders and gatekeepers of science, technology, engineering, mathematics, and medicine (STEMM) organizations, higher education, and human resource offices can improve minoritized people's individual and interpersonal experiences in STEMM educational and professional environments through the following practices: 1. Improve numerical diversity through the admission, hiring, and inclusion of minoritized individuals at all levels of an organization: a. Establish information systems across institutions using common metrics for comparison purposes to collect data, track success, and identify areas of numeric disparities. Results should be transparent, up-to-date, and accurate. b. Hire more minoritized individuals, especially in positions where minoritized role models are often missing (e.g., leadership, mentorship), with the aim of building a critical mass. c. Determine if the institutional diversity statement reflects the reality of the institutional environment, and directly address discrepancies. d. Adapt curriculum, physical environment, media stories, and other content to incorporate more examples of minoritized role models.
NASEM (2023a) Rec5.2	Leaders and gatekeepers of science, technology, engineering, mathematics, and medicine (STEMM) organizations, higher education, and human resource offices can improve minoritized people's individual and interpersonal experiences in STEMM educational and professional environments through the following practices: 1. Create and provide continued investment in evidence-based programs that connect minoritized individuals to ingroup peers, institutional resources, and professional networks. These investments require significant expertise in their designs and execution, and they may not yield immediate results; however, they can increase a sense of welcome and belonging through the ability to connect with individuals from similar racial and ethnic backgrounds. Types of programs may include the following types of resources: a. Summer bridge programs. b. Living-learning communities.

continued

TABLE F.A-1 Continued

Report and Recommendation Number	Recommendation Text
	c. Peer and near-peer mentorship programs. d. Active work to form relationships with national-level affinity societies (e.g., Society for the Advancement of Chicanos and Native Americans in STEM, National Society for Black Engineers, American Indian Science and Engineering Society, etc.), create local chapters, and provide opportunities for minoritized individuals to connect with them.
NASEM (2023a) Rec5.3	Leaders and gatekeepers of science, technology, engineering, mathematics, and medicine (STEMM) organizations, higher education, and human resource offices can improve minoritized people's individual and interpersonal experiences in STEMM educational and professional environments through the following practices: 1. Create and provide continued investment in programs that facilitate working relationships between minoritized individuals and high-status professionals: a. Create and invest in mentorship programs, while hiring more minoritized faculty. b. Conduct additional research examining the roles of other high-status individuals such as champions and sponsors on fostering STEMM careers for minoritized individuals.
NASEM (2023a) Rec5.4	Leaders and gatekeepers of science, technology, engineering, mathematics, and medicine (STEMM) organizations, higher education, and human resource offices can improve minoritized people's individual and interpersonal experiences in STEMM educational and professional environments through the following practices: 1. Develop interpersonal environments and institutional norms that promote inclusion, dignity, belonging, and affirmations of kindness: a. Actively recognize minoritized individuals' contributions to STEMM across multiple mediums such as portraits, media stories, awards, etc. b. De-center White professional norms in culture, dress, and appearance. c. Conduct additional research examining which features of the physical environment are most likely to promote sustainable antiracism, diversity, equity, and inclusion in STEMM. d. Emphasize and recognize the importance of communal values in STEMM work. e. Redesign STEMM curriculum to incorporate Indigenous ways of knowing, and actively involve Indigenous communities in the development of this process. f. Create cultural norms that communicate the strengths and struggles of minoritized groups. g. Provide access to culturally responsive mental health providers or resources with experience in addressing racial stress, trauma, and aggressions for minoritized individuals who have experienced distress and would like to pursue these options. h. Conduct biannual "cultural audits" to determine if the institution is fostering an environment of inclusion.
NASEM (2023a) Rec5.5	Leaders and gatekeepers of science, technology, engineering, mathematics, and medicine (STEMM) organizations, higher education, and human resource offices can improve minoritized people's individual and interpersonal experiences in STEMM educational and professional environments through the following practices: a. Use evidence-based design and implementation practices to build curriculum initiatives that increase access to discovery, including, for example, course-based research experiences.
NASEM (2023a) Rec6.1	Leaders of science, technology, engineering, mathematics, and medicine (STEMM) organizations and directors of human resource offices can improve minoritized people's individual and interpersonal experiences in STEMM educational and professional environments through the following practices: • Create organizational-level or unit-level information systems to collect data on the decisions of gatekeepers. Data collected may include, but not be limited to hiring, admissions, promotion, tenure, advancement, and awards. Data should be examined in the aggregate to identify patterns of bias exhibited by gatekeepers based on race and ethnicity.

TABLE F.A-1 Continued

Report and Recommendation Number	Recommendation Text
	• Include responsibilities related to advancing antiracism, diversity, equity, and inclusion in leadership role descriptions and requirements for advancement into management. • Develop systems with more widely shared, inclusive decision-making processes and shared authority over the allocation of resources, which should limit the negative consequences that occur when gatekeeping is concentrated in a select few individuals.
NASEM (2023a) Rec6.2	Additional research is needed to examine the psychological impacts of perpetuating racism from the perspective of the gatekeeper in science, technology, engineering, mathematics, and medicine.
NASEM (2023a) Rec7.1	Gatekeepers who manage teams, including but not limited to principal investigators and heads of laboratories and research groups, should be intentional about creating the following conditions. These can support positive team performance outcomes and help reduce instances of interpersonal bias. • Increase the numeric representation of minoritized individuals on teams, by working toward building a critical mass, a necessary but not sufficient attribute of building an inclusive environment. • Create team norms that centralize a positive climate, in which it is known that all team members, including minoritized individuals, are supported, heard, and respected. • Develop interdependent teams in which everyone is cooperating and working toward an established common goal. • Ensure that team members feel psychologically safe on the team, and if not, identify the specific factors that are preventing psychological safety and work to address them. • Work to promote equal status among team members. Remove asymmetric power differentials among team members, especially between White team members and minoritized team members. • Incorporate greater diversity in developing team roles, and make sure all team members have clear roles and expectations, including access to professional development and pathways to advancement.
NASEM (2023a) Rec8.1	Organizational leaders should take action to redress both individual bias and discrimination as well as organizational processes that reproduce harm and negative outcomes for peole from minoritized racial and ethnic groups at critical points of access and advancement. This action should include a review of evaluation criteria and decision-making practices (i.e., in admissions, hiring and wage-setting, and promotion and advancement) to understand if and to what degree existing standards perpetuate underlying racial and ethnic inequities. • Admissions offices at colleges and universities, as well as admissions decision makers in graduate programs, should assess the alignment or divergence of their current admissions policies and criteria with values of antiracism, diversity, equity, and inclusion, and develop holistic admissions strategies that offer a systematic, contextualized evaluation of applicants on multiple dimensions. • Hiring managers, directors of human resources, and supervisors should measure and review the application, offer, and acceptance rates in their organization, as well as the salaries, resource packages, and academic tracks and titles of new hires, for instances of racial and ethnic discrimination in the hiring process. As a result, these leaders should, as appropriate, implement proactive outreach and recruitment to increase applications from people from minoritized racial and ethnic groups, trainings and resources to eliminate bias in the hiring process for managers, and updated policies to reduce bias and discrimination in setting wages. • Directors of human resources and supervisors should measure, evaluate, and address the presence of bias and discrimination in rewards, key assignments and promotion, the proportion of people from historically minoritized backgrounds leaving their positions and their reasons for doing so, and the access to culturally relevant mentorship for students and employees.

continued

TABLE F.A-1 Continued

Report and Recommendation Number	Recommendation Text
NASEM (2023a) Rec8.2	Leaders, managers, and human resource departments in science, technology, engineering, mathematics, and medicine organizations should anticipate resistance to antiracism, diversity, equity, and inclusion efforts and investigate with rigorous empirical tools, the impacts of training on different types of antiracism, diversity, equity, and inclusion outcomes (hiring, climate, promotion, retention, leadership roles, resource allocation).
NASEM (2023a) Rec8.3	Presidents, chief executive officers, and leaders of science, technology, engineering, mathematics, and medicine organizations, including those in higher education and the private sector, should use a framework (such as those listed below) to evaluate the institution's values and norms and identify specific ways to address norms that impede diversity and promote a culture that is genuinely accessible and supportive to all. These top-level leaders should work with managers, supervisors, and other mid-level leaders who influence the local culture within organizations and can be a critical part of implementation. The evaluation should include review of: • Institutional policies and practices for instances of bias with regard to race and ethnicity; • Policies and practices for entrance into the organization (admissions, hiring, or nomination), advancement (promotion and tenure), and other rewards; • Analysis of resource allocation by race and ethnicity such as wages and bonuses, mentorship, professional development opportunities, physical materials or assets, and other items or forms of support; • Mentorship, training, and professional development opportunities to build skills specific to supporting Black students, Indigenous students, and students and trainees from historically minoritized racial and ethnic groups; • Culturally-aware mentorship and management training for supervisors, administrators, and other leaders; and • The results of regular climate surveys to evaluate the working conditions and environment.
Origins, Worlds, and Life: Planetary Science and Astrobiology in the Next Decade (NASEM 2022b)	
NASEM (2022b) Rec1	NASA PSD and NSF with its wide experience with programs such as the Louis Stokes Alliances for Minority Participation (LSAMP) and Organizational change for Gender Equity in STEM Academic Professions (ADVANCE), should make it a priority to obtain currently lacking evidence about fundamental aspects of the state of planetary science and astrobiology communities. NASA PSD and NSF should engage with experts to undertake data collection on 3- to 5-year cycles with a focus on obtaining accurate data on: • The size and identity of PS (Planetary Science) and AB (Astrobiology), given their deeply interdisciplinary nature, • The demographic composition of PS&AB along all relevant dimensions, and • The workplace climate at NASA PSD and affiliated institutions, as well as the social issues that facilitate or impede scientific progress in PS&AB.
NASEM (2022b) Rec2	NASA PSD should adopt the view that bias can be both unintentional and pervasive. To address potential bias issues, NASA should: • Seek the expertise of behavioral scientists to develop methods for analyzing its decision making practices and procedures (e.g., advertising, recruiting, selection, hiring, onboarding, promotion, compensation, managing teams, fieldwork, and mission planning). • Determine where bias does, and does not, play a role and work with the evidence to reduce and eliminate bias from its procedures wherever it is found to exist. • Proactively engage with the PS&AB community in the development of creative initiatives to uncover and mitigate bias in existing processes. • Consider evidence-based bias education for itself and associated institutions. Honest discussions of policies and practices that no longer serve the functioning of modern scientific enterprises should be sought with enthusiasm that mirrors the enthusiasm NASA PSD brings to its scientific innovation. • Follow education at a foundational level with discussions among individuals within NASA PSD with authority to effect change.

TABLE F.A-1 Continued

Report and Recommendation Number	Recommendation Text
	• Include regular focus on different aspects of the issues, e.g., opportunities for tenure of NASA-funded PS&AB members in academia, advancement to senior civil service positions at NASA centers, peer reviewed research funding opportunities, addressing climate issues, participation in space mission teams, keynote presentation opportunities at scientific conferences, and awards by professional societies. • Publicize the procedures and policies that have been reviewed and transformed each year.
NASEM (2022b) Rec3a	NASA PSD (Planetary Science Division) should revisit the centralization policy on public engagement and consider mechanisms to support direct engagement of planetary scientists with members of society, particularly students in STEM fields.
NASEM (2022b) Rec3b	PSD should regularly evaluate programs that enhance participation of students and faculty from URC's; fellowship programs that facilitate engagement of NASA-funded planetary scientists and astrobiologists with faculty at URC institutions; and mechanisms for supporting education and outreach as an integral part of research via, e.g., the inclusion of outreach activities as optional add-ons to R&A grants, or as a requirement for missions or cooperative agreements.
NASEM (2022b) Rec3c	NASA PSD should strengthen and expand programs aimed at educating the community about the mission proposal process (e.g., PI Launchpad) and actual mission operations (e.g., participating scientist programs), particularly to reach out to URCs. Providing access to personnel or tools that can help guide investigators through the process should be considered, including participation as contributing members of the mission teams.
NASEM (2022b) Rec3d	NASA and PSD should reinstate the Harriett G. Jenkins and similar predoctoral fellowship projects as part of an effort to retain members of URC in the fields of PS&AB prior to them reaching existing pinch points at which substantial decline in URC representation is seen in both fields.
NASEM (2022b) Rec4a	PSD should implement Codes of Conduct (CoC) for funded field campaigns, conferences, and missions, and should expect acknowledgement of receipt and understanding. The CoC should be codified, reviewed, and updated at regular intervals. An effective CoC should outline expected behavior, explain unacceptable behavior, explain how policies will be enforced, provide clear instructions on how to report incidents, and explain consequences of violations. The process should demonstrate sensitivity to the difficulty of bringing forward accusations and to the rights of the accused.
NASEM (2022b) Rec4b	NASA PSD and affiliated institutions should clearly identify a Point of Contact or ombudsperson as part of the CoC to provide access to individuals who experience violations to the CoC. The egregious nature of the sexual harassment reported in field work requires immediate attention by NASA.
Pathways to Discovery in Astronomy and Astrophysics for the 2020s (NASEM 2023b)	
NASEM (2023b) Rec1	Funding agencies should increase funding incentives for improving diversity among the college/university astronomy and astrophysics faculty—for example, by increasing the number of awards that invest in the development and retention of early-career faculty and other activities for members of underrepresented groups.
NASEM (2023b) Rec2	NASA, NSF, and DOE should reinvest in professional workforce diversity programs at the division/directorate levels with purview over astronomy and astrophysics. Because academic pipeline transitions are loss points in general, supporting the creation and continued operation of "bridge" type programs across junctures in the higher-education pipeline and into the professional ranks appear especially promising.
NASEM (2023b) Rec3	NSF, NASA, and DOE should implement undergraduate and graduate "traineeship" funding, akin to the NIH MARC and NIH "T" training grant programs, to incentivize department/institution-level commitment to professional workforce development, and prioritize interdisciplinary training, diversity, and preparation for a variety of career outcomes.

continued

TABLE F.A-1 Continued

Report and Recommendation Number	Recommendation Text
NASEM (2023b) Rec4	NASA and NSF should continue and increase support for postdoctoral fellowships that provide independence while encouraging development of scientific leaders who advance diversity and inclusive excellence (e.g., NASA Hubble Fellows program, NSF Astronomy and Astrophysics Postdoc program).
NASEM (2023b) Rec5	NASA, NSF, DOE, and professional societies should ensure that their scientific integrity policies address harassment and discrimination by individuals as forms of research/ scientific misconduct.
NASEM (2023b) Rec6	NASA, NSF, and DOE should implement a cross-agency committee or working group tasked with establishing a consistent format and policy for regularly collecting, evaluating, and publicly reporting demographic data and indicators pertaining at a minimum to outcomes of proposal competitions.
NASEM (2023b) Rec7	NASA, DOE, and NSF should consider including diversity—of project teams and participants—in the evaluation of funding awards to individual investigators, project and mission teams, and third-party organizations that manage facilities. Approaches would be agency specific, and appropriate to the scale of the projects.
NASEM (2023b) Rec8	The astronomy community should, through the American Astronomical Society in partnership with other major professional societies (e.g., American Physical Society, American Geophysical Union, International Astronomical Union), work with experts from other experienced disciplines (such as archaeology and social sciences) and representatives from local communities to define a Community Astronomy model of engagement that advances scientific research while respecting, empowering and benefiting local communities.
NASEM (2021) Rec11	The astronomy community should increase the use of remote observing, hybrid conferences, and remote conferences, to decrease travel impact on carbon emissions and climate change.
Enhancing the Effectiveness of Team Science (NRC 2015)	
NRC (2015) Rec8	Funders should require proposals for team-based research to present collaboration plans and provide guidance to scientists for the inclusion of these plans in their proposals, as well as guidance and criteria for reviewers' evaluation of these plans. Funders should also require authors of proposals for interdisciplinary or transdisciplinary research projects to specify how they will integrate disciplinary perspectives and methods throughout the life of the research project.

NOTE: Acronyms are defined in Appendix H.

REFERENCES TO ANNEX F.A

NASEM (National Academies of Sciences, Engineering, and Medicine). 2020. *Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics: A Midterm Assessment*. The National Academies Press. https://doi.org/10.17226/25668.

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G

Technical, Risk, and Cost Evaluation

G.1 OVERVIEW OF THE TRACE PROCESS

In carrying out its task for this solar and space physics decadal survey, an independent assessment of the technical readiness and life-cycle costs was needed for several high-priority, relatively high-cost, mission concepts under consideration for inclusion in a recommended comprehensive strategy. For this task, the National Academies of Sciences, Engineering, and Medicine contracted with The Aerospace Corporation to provide an independent evaluation. The corporation used the technical, risk, and cost evaluation (TRACE) process for its evaluation.

TRACE provides a common framework for the programmatic evaluation of concepts under consideration for decadal surveys and other studies by the National Academies (NASEM 2023a,b). A detailed discussion of the TRACE process is provided in the 2023 astronomy and astrophysics decadal survey report, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*.[1] This decadal survey followed a process similar to that of the astronomy and astrophysics decadal survey, but with a few key differences. Notably, it focused exclusively on space-based projects. Additionally, unlike the astronomy and astrophysics decadal study, which used separate panels for determining science priorities and project priorities, this survey for solar and space physics consolidated these functions within a single panel.

In developing the lists of mission concepts to provide to the steering committee, each of the science study panels—the Panel on Physics of Ionospheres, Thermospheres, and Mesospheres; the Panel on the Physics of Magnetospheres; and the Panel on Physics of the Sun and Heliosphere—began with the identification of priorities for solar and space physics science. This identification was informed by literature reviews, feedback from community meetings and workshops, and especially responses from a request for information.[2] In response to this request, the panels received 450 community input papers.

While the steering committee provided general guidance to the panels, they had considerable flexibility in the processes they employed to gather information and develop their mission concepts. After deliberations, each of the panel forwarded a short list of concepts that address the science priorities to the steering committee. The steering

[1] See Appendix O in NASEM (2023a).

[2] See links at https://www.nationalacademies.org/our-work/decadal-survey-for-solar-and-space-physics-heliophysics-2024-2033. At its highest level, the request for information asked respondents to 1. Provide an overview of the current state of solar and space physics science and applications; 2. Describe the highest-priority science goals to be addressed in the period of the survey; 3. Develop a comprehensive ranked research strategy that provides an ambitious but realistic approach to address these goals that includes ground- and space-based investigations as well as data and computing infrastructure to support the research strategy; and 4. Assess the state of the profession.

committee, in turn, selected 12 mission concepts that went through the full TRACE process. A 13th mission concept went through the technical and risk assessment but not the cost assessment.

For each mission concept that went through all or part of TRACE, details about the design (e.g., mission design, instrument, bus details) were gathered in coordination with the panels. The information was drawn from the community input papers, mission concept study reports when available, and additional requests for information to members of the community. The tradespace of technical solutions was then narrowed, and a baseline design was evaluated.

The TRACE process had specific steps that focused on technical aspects, cost, and schedule. First, an evaluation of the technical readiness and risk identification was carried out. Risks may be associated with different factors—including but not limited to instrument maturity, spacecraft bus accommodation, mission design, and operations—and are often associated with technology development. Some of the concepts evaluated are satellite constellations, which have unique challenges associated with multiple builds and rideshare accommodations. Individual risks were then collated to form an overall risk rating for the mission concept, which was assigned as a qualitative color rating of green (low risk), yellow (medium risk), or red (high risk).

A cost evaluation was then performed for each mission concept. The identified risks were quantified in terms of the effect on the estimated cost, based on the technical evaluation and historical data. The spacecraft and instrument hardware costs were estimated by Aerospace Corporation using standard cost evaluation methods, including analogies, models, and previous cost data. Cost estimates were performed down to the standard Level 3 Work Breakdown Structure (WBS) using National Aeronautics and Space Administration guidelines. A probabilistic cost risk analysis was performed using a triangular distribution of costs from least likely to most likely for each WBS element. Launch vehicle (LV) cost estimates were based on the technical assessment of the number and size of launch vehicles required and matched to candidate launch vehicles in the current Launch Services Program catalog. Future LV costs are unknown; therefore, current costs were used uniformly to put the mission concepts on an equal footing. The results of this cost assessment are documented in an “S-curve,” and a recommended cost reserve was estimated. Budget threats identified from the technical risk assessment were then added to the cost (Bitten et al. 2013).

A schedule analysis was also performed. All mission concepts were assumed to have a start date of 2025, except for Interstellar Probe, which requires significant technology development, driving an assumed 2029 start date. A draft mission schedule was developed considering science constraints (e.g., solar cycle), technology development, historical build duration data, special considerations such as multiple spacecraft builds, and the science operations timeline. The schedule risk for development (Phases A–D) was then assessed and documented in a schedule S-curve with schedule reserves estimated.

The analyses were then aggregated into a budget profile for each mission concept, and the profiles were validated and cross-checked through a series of reviews. Internal reviews were held at Aerospace Corporation with experienced personnel; they included an examination of the details of each TRACE to ensure that each concept was evaluated consistently. After the internal review, the results were presented to panel and steering committee members. Any disconnects in the science or mission assumptions were identified and resolved. In some cases, further consultation with the panels produced a “descope” of the concept, and an update to the budget analysis was performed.

G.2 SYNOPSIS OF TRACE RESULTS

G.2.1 The Selected Mission Concepts

As noted above, the steering committee selected 12 mission concepts for the full TRACE process and an additional one that went through the technical and risk assessment but not the cost assessment:

- Multipoint Comprehensive Eruptive Mission (MCEM)
- Ecliptic Heliospheric Constellation (ECH)
- Solar Polar Orbiter (SPO)
- Heliospheric Dynamics Transient Constellation (HDTC)
- Interstellar Probe
- Resolve

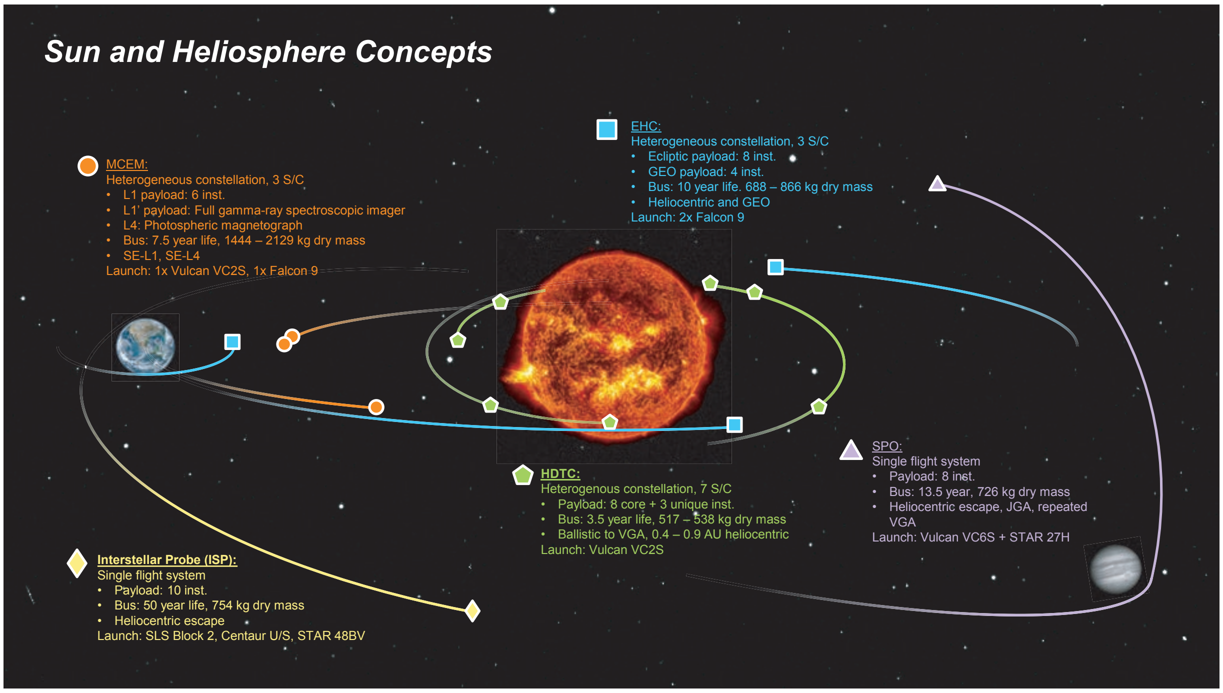


FIGURE G-1 Notional Sun and heliosphere mission concepts evaluated using technical, risk, and cost evaluation (*Clockwise from Top Left*): MCEM (Multipoint Comprehensive Eruptive Mission), ECH (Ecliptic Heliospheric Constellation), SPO (Solar Polar Orbiter), HDTC (Heliospheric Dynamics Transient Constellation), and Interstellar Probe.
NOTE: GEO, geosynchronous orbit; inst., instruments; JGA, Jupiter gravity assist; L1 and L4, Lagrange points 1 and 4; S/C, spacecraft; SE-L1, solar ecliptic Lagrange point 1; SLS, Space Launch System; VGA, Venus gravity assist.
SOURCES: Composed by The Aerospace Corporation; Sun image from NASA Goddard; Jupiter image from NASA; Star field background from NASA/JPL.

- Interhemispheric Circuit (I-Circuit)
- Low-Altitude Ionosphere and Thermosphere In Situ Researcher (LAITIR)
- Buoyancy Restoring-Force Atmospheric-Wave Vertical-Propagation Observatory (BRAVO)
- Synchronized Observations of Upflow, Redistribution, Circulation, and Energization (SOURCE)
- Observatory for Heteroscale Magnetosphere-Ionosphere Coupling (OHMIC)
- Comprehensive Observations of Magnetospheric Particle Acceleration, Sources, and Sinks (COMPASS)
- Links: Links between regions and scales in geospace

Figures G-1 through G-3 show a summary of these 12 mission concepts, by subdiscipline. Quad-chart descriptions for each mission concept are shown below in Section G.2.5, in Figures G-6 through G-18.

G.2.2 Cost Analyses

A cost comparison for all mission concepts is shown in Figure G-4. Costs are divided into development and operations costs, which include all pre-Phase A technology development (if applicable) and Phases A–F[3]; LV costs; and budget threats, which were monetized. All costs are shown in fiscal year (FY) 2024 dollars. Budget threats are based on identified risks that could drive the cost above the baseline estimate.

[3] Phase A, preliminary analysis; Phase B, definition; Phases C/D, design and development; Phase E, operations; Phase F, closeout.

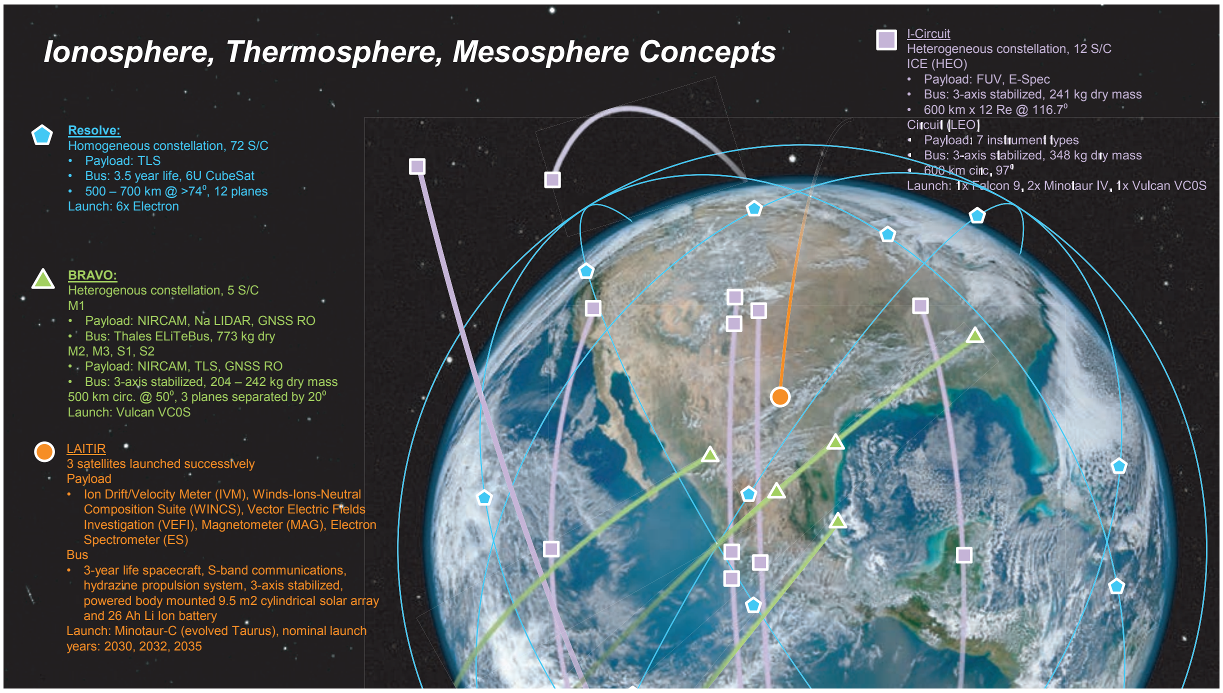


FIGURE G-2 Notional ionosphere, thermosphere, mesosphere concepts evaluated using technical, risk, and cost evaluation (*Clockwise from the Top Left*): Resolve, I-Circuit (Interhemispheric Circuit), LAITIR (Low Altitude Ionosphere and Thermosphere In Situ Researcher), and BRAVO (Buoyancy Restoring-force Atmospheric-wave Vertical-propagation Observatory).
NOTE: Ah, Amp-hours; E-spec, electron spectrometer; FUV, far ultraviolet; GNSS RO, Global Navigation Satellite System Radio Occultation; HEO, highly elliptical orbit; NIRCAM, near infrared camera; TLS, terahertz limb sounder.
SOURCES: Composed by The Aerospace Corporation; Earth image from NASA; Star field background from NASA/JPL.

The mission concepts evaluated for this decadal survey included multiple large, often heterogenous constellations; multiple concepts with heliocentric, interplanetary, or interstellar destinations; and longer operations phases. As such, the estimated cost of some concepts is commensurately higher than historical heliophysics missions, although the cost of the survey-prioritized Links and SPO notional concepts are estimated at \$1.3–\$1.4 billion. These costs are comparable to recent missions such as, Parker Solar Probe (\$1.8 billion), Magnetosphere MultiScale (MMS) mission (\$1.5 billion), Solar Dynamics Observatory (SDO) (\$1.3 billion), and Van Allen Probes (\$0.9 billion), when measured in FY 2024 dollars.

G.2.3 Risk Ratings

Risk ratings by subdiscipline are shown in Figure G-5 and reflect the degree of technical difficulty for the mission concept. All the heliophysics mission concepts that were evaluated fell into one of three categories:

- Medium-low, green: moderate new development, adequate margins, and/or moderate risk to achieve major mission objectives as proposed;
- Medium, yellow: medium new development, adequate to optimistic margins, and/or medium risk of achieving major mission objectives as proposed; or
- Medium-high, orange: significant new development, optimistic to negative margins, or significant risk of achieving major mission objectives.

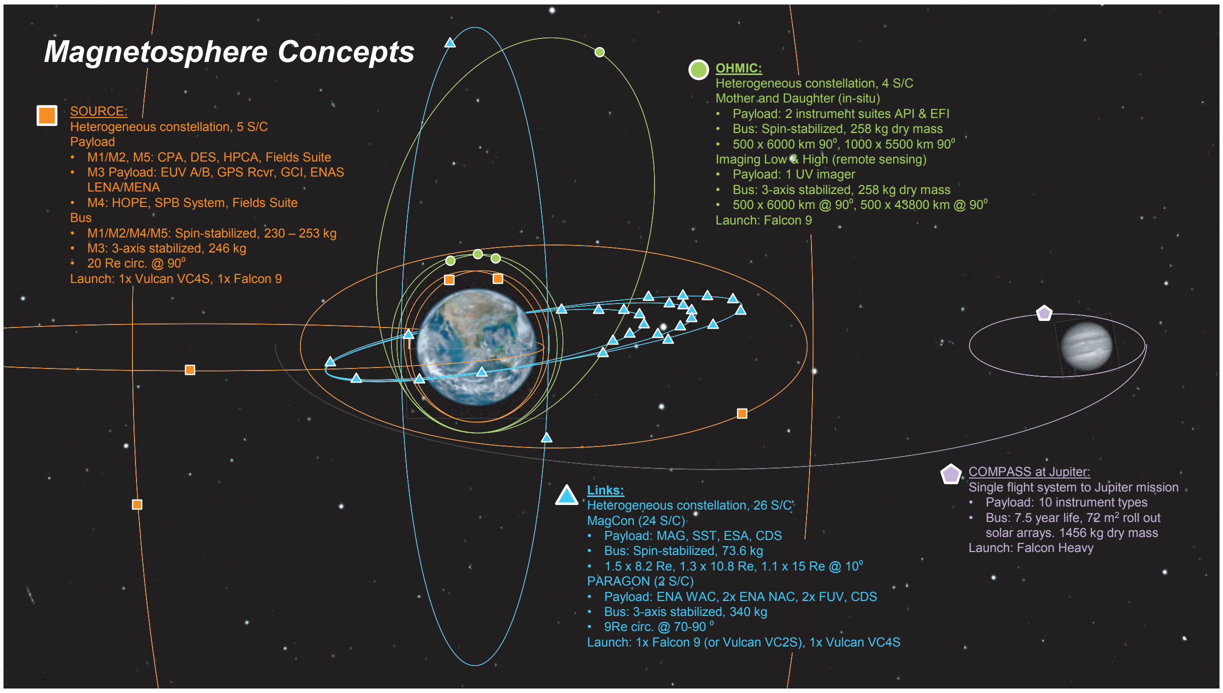


FIGURE G-3 Notional magnetosphere mission concepts evaluated using technical, risk, and cost evaluation (*Clockwise from Top Left*): SOURCE (Synchronized Observations of Upflow, Redistribution, Circulation, and Energization), OHMIC (Observatory for Heteroscale Magnetosphere-Ionosphere Coupling), COMPASS (Comprehensive Observations of Magnetospheric Particle Acceleration, Sources, and Sinks), and Links: Links between regions and scales in geospace.
NOTE: API, Auroral Plasma Instrument; CDS, charge discharge sensor; CPA, Core Plasma Analyzer; DES, Dual Electron Spectrometer; EFI, Electromagnetic Fields Instrument; ENA, energetic neutral atom; ESA, electrostatic analyzer; EUV, extreme ultraviolet; GCI, Geocoronal Imager; HPCA, Hot Plasma Composition Analyzer; MAG, magnetometer; MagCon, magnetospheric constellation; PARAGON, Plasma Acceleration, Reconfiguration, and Aurora Geospace Observation Network; Rcvr, receiver; SST, solid state telescope; UV, ultraviolet.
SOURCES: Composed by The Aerospace Corporation; Earth image from NASA; Star field background from NASA/JPL.

The Sun and heliosphere concepts were rated as relatively higher risk among the concepts studied, several of which require significant instrument technology development. Most ionosphere, thermosphere, and mesosphere and magnetosphere concepts are relatively lower risk, ranging between medium and medium-low. The Resolve, HDTC, and Links risk ratings are driven by development, deployment, and the operations of large constellations. COMPASS at Jupiter, HDTC, and SPO are interplanetary mission concepts with challenging flight environments and operational challenges. The interplanetary nature of most of the Sun and heliosphere missions is the primary driver for the higher-risk ratings.

G.2.4 Space Weather Enhancement Options

In addition to evaluation of the 13 selected mission concepts, the steering committee requested suggestions for space weather enhancements from the Panel for Space Weather Science and Applications. A detailed summary of space weather evaluations and enhancements is included in an annex to the panel report (see Appendix E). The Aerospace Corporation carried out a cost evaluation for a selection of those enhancements. The analysis found that space weather enhancements had only modest effects on project schedules and costs, with cost increases

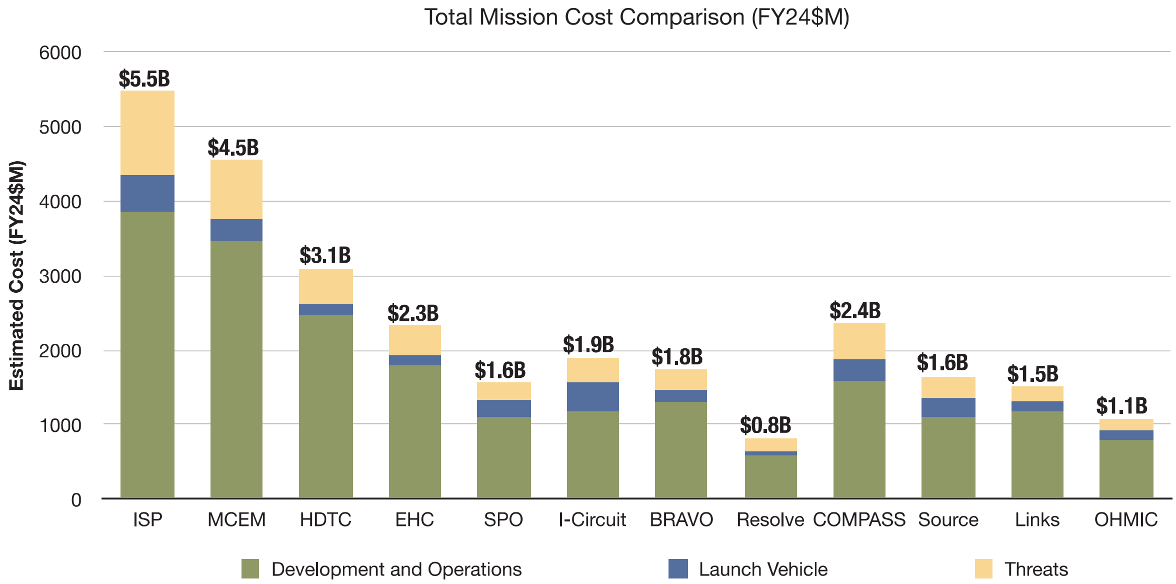


FIGURE G-4 Heliophysics mission concept cost comparison, in FY 2024 dollars, in order of most to least estimated cost by discipline area.
NOTES: Development and operations includes phases from pre-Phase A through Phase F, excluding launch vehicle cost and threats, which are broken out separately. Threats are based on identified risks that could drive the cost above the baseline estimate. (Sun and Heliosphere) ISP, Interstellar Probe; MCEM, Multipoint Comprehensive Eruptive Mission; HDTC, Heliospheric Dynamics Transient Constellation; EHC, Ecliptic Heliospheric Constellation; SPO, Solar Polar Orbiter; (Ionosphere, Thermosphere, Mesosphere) I-Circuit, Interhemispheric Circuit; BRAVO, Buoyancy Restoring-Force Atmospheric-Wave Vertical-Propagation Observatory; Resolve; (Magnetosphere) COMPASS, Comprehensive Observations of Magnetospheric Particle Acceleration, Sources, and Sinks; SOURCE, Synchronized Observations of Upflow, Redistribution, Circulation, and Energization; Links; OHMIC, Observatory for Heteroscale Magnetosphere-Ionosphere Coupling.
SOURCE: Created based on TRACE data provided by The Aerospace Corporation.

ranging from $1 million to $36 million. The panel found that certain destinations are good targets for specific space weather enhancements. Examples are enhanced Global Navigation Satellite System receiver firmware to enable measurements of total electron content in low Earth orbit, charge-discharge sensors in medium and high Earth orbits, and sensors to measure solar energetic particles outside of Earth orbit.

G.2.5 Overall TRACE Results

A summary of TRACE results is shown in Table G-1. Quad-chart descriptions for the 13 selected mission concepts are shown in Figures G-6 through G-18, in order of most to least estimated cost by discipline area. LAITIR, which did not undergo cost evaluation, is included at the end.

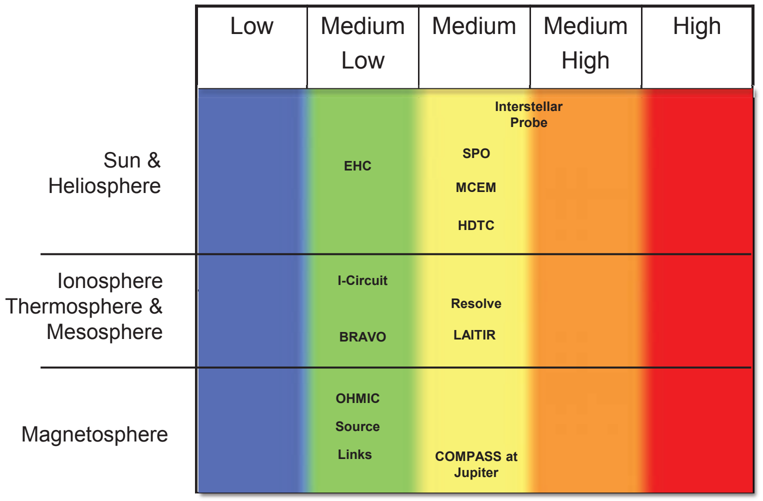


FIGURE G-5 Heliophysics mission concept risk ratings.
NOTE: BRAVO, Buoyancy Restoring-Force Atmospheric-Wave Vertical-Propagation Observatory; COMPASS, Comprehensive Observations of Magnetospheric Particle Acceleration, Sources, and Sinks; EHC, Ecliptic Heliospheric Constellation; HDTC, Heliospheric Dynamics Transient Constellation; I-Circuit, Interhemispheric Circuit; ISP, Interstellar Probe; Links, links between regions and scales in geospace; MCEM, Multipoint Comprehensive Eruptive Mission; OHMIC, Observatory for Heteroscale Magnetosphere-Ionosphere Coupling; SOURCE, Synchronized Observations of Upflow, Redistribution, Circulation, and Energization; SPO, Solar Polar Orbiter.
SOURCE: Created by The Aerospace Corporation.

TABLE G-1 Summary of Technical, Risk, and Cost Evaluation Results

Mission Concept	Technical Risk Rating	Assumed Launch Date	Mission Concept Cost Excluding LV, Phases A–F (millions of FY2024 dollars)[a]	LV Cost (millions of FY2024 dollars)	Concept Description Section[b]
Interstellar Probe[c]	Med-high	2036	$4,185	$1,592	B.5.2.1
MCEM	Medium	2033/2034	$4,266	$281	B.5.2.1
EHC	Med-low	2034	$2,216	$150	B.5.2.1
SPO	Medium	2032	$1,312	$245	B.5.2.1
HDTC	Medium	2033	$2,926	$161	B.5.2.1
BRAVO	Med-low	2032	$1,588	$161	D.6.2.1
Resolve	Medium	2034	$705	$52	D.6.2.2
I-Circuit	Med-low	2031	$1,489	$405	D.6.2.3
COMPASS at Jupiter	Medium	2031	$2,076	$291	C.5.2.1
Links	Med-low	2032	$1,390	$150	C.5.2.1
OHMIC	Med-low	2032	$978	$100	C.5.2.1
SOURCE	Med-low	2032	$1,429	$220	C.5.2.1
LAITIR	Medium	2030/2032/2035	Not costed	Not costed	D.6.2.4

[a] Assuming Phase B start in 2025.
[b] Mission concepts are described in detail in Appendixes B-D (science panel reports).
[c] Phase B start in 2029.
NOTE: BRAVO, Buoyancy Restoring-Force Atmospheric-Wave Vertical-Propagation Observatory; COMPASS, Comprehensive Observations of Magnetospheric Particle Acceleration, Sources, and Sinks; EHC, Ecliptic Heliospheric Constellation; FY24, fiscal year 2024; HDTC, Heliospheric Dynamics Transient Constellation; I-Circuit, Interhemispheric Circuit; LAITIR, Low-Altitude Ionosphere and Thermosphere In Situ Researcher; Links, links between regions and scales in geospace; LV, launch vehicle; MCEM, Multipoint Comprehensive Eruptive Mission; OHMIC, Observatory for Heteroscale Magnetosphere-Ionosphere Coupling; SOURCE, Synchronized Observations of Upflow, Redistribution, Circulation, and Energization; SPO, Solar Polar Orbiter.

Interstellar Probe Mission

Interstellar Probe:

Interstellar Probe Mission
(reaching ~ 100 AU in 14.8 years and ~ 344 AU in 50 years)

Key Features:

- Probe
  - ***Payload (10 instruments):*** *Magnetometer (MAG), Plasma Wave Subsystem (PWS), Plasma Subsystem (PLS), Pick-Up Ions (PUI), Energetic Particle Subsystem (EPS), Cosmic Ray Subsystem (CRS), Interstellar Dust Analyzer (IDA), Neutral Mass Spectrometer (NMS), Energetic Neutral Atom (ENA) Camera, Lyman-Alpha Spectrograph (LYA)*
  - ***Flight System:*** *50-year life spacecraft, X-band communications up to 1000 AU, chemical propulsion system, redundant avionics, flight software autonomy for fault management and data management, capable of operating in spin or 3-axis pointing modes, powered by 2 x Next Generation Radioisotope Thermal Generators (NGRTGs)*
- Launch: **SLS Block 2 with Centaur + STAR 48BV,** nominal launch year: 2036
- Mission Design: **Heliocentric escape** trajectory, C3 = 304 km^2/s^2 with Jupiter Gravity Assist (**JGA**)

Scientific Objectives:

- **Primary Goal:** Understand our heliosphere as a habitable astrosphere and its home in the galaxy
- **Key Science Questions Addressed:**
  - How is our heliosphere upheld by the physical processes from the Sun to the Very Local Interstellar Medium (VLISM)?
  - How do the Sun's activity as well as the interstellar medium and its possible inhomogeneity influence the dynamics and evolution of the global heliosphere?
  - How do the current VLISM properties inform our understanding of the evolutionary path of the heliosphere?

Key Challenges:

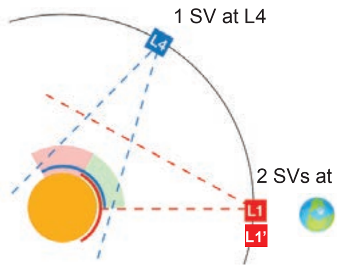
- Adequately assuring a 50-year design life for flight system within available resources
- Potential growth in flight system launch mass and uncertainty in performance of heavy booster
- Long-term performance and lifetime of NGRTG power system
- Uncertainties in mission-specific instrument modifications and updates
- Uncertainties in long range, long-term operations

Technical Risk Rating is Medium-High

FIGURE G-6 Mission overview for Interstellar Probe mission concept.
SOURCES: Composed by The Aerospace Corporation; Background image from Johns Hopkins University Applied Physics Laboratory.

Multipoint Comprehensive Eruptive Mission (MCEM)

Overview:



MCEM Constellation (3 satellites)

Key Features:

- L1
  - ***Payload (6 instruments):*** *Photospheric Magnetograph, EUV Filtergram Imager, Soft X-ray (SXR) Spectroscopic Imager, Hard X-ray (HXR) Spectroscopic Imager, Energetic Neutral Atom (ENA) Spectroscopic Imager, Lyman-alpha Hanle Coronagraph*
  - ***Flight System:*** *7.5 year lifetime, Optical and X-Band communications, 3-axis stabilized, 1157 W deployed solar array and 40 Ah Li Ion battery, bipropellant propulsion system*
- L1'
  - ***Payload (1 instrument):*** *Full Gamma-ray Spectroscopic Imager*
  - ***Flight System:*** *7.5 year lifetime, Optical and X-Band communications, 3-axis stabilized, 1157 W deployed solar array and 40 Ah Li Ion battery, bipropellant propulsion system*
- L4
  - ***Payload (1 instrument):*** *Photospheric Magnetograph*
  - ***Flight System:*** *7.5 year lifetime, Optical and X-Band communications, 3-axis stabilized, 1157 W deployed solar array and 40 Ah Li Ion battery, bipropellant propulsion system*
- Launch: L1/L1': Vulcan VC2S to -0.5 km^2/s^2, L4: Falcon 9 to -0.5 km^2/s^2
- Mission Design/Constellation: Sun-Earth L1 (2 space vehicles) and L4 (1 space vehicle)

Scientific Objectives:

- Science Goal: Understand the causal links between the Sun's evolving 3D magnetic field and all forms of energy release and transport in the corona
- Science Questions:
  - *In 3D, where, how, and how much is magnetic energy stored prior to an impulsive event; and what magnetic configurations determine the timing, location, and extent of free energy release? What are the signatures of this release?*
  - *In 3D, where, how, and how much is magnetic energy released to drive coronal heating and solar wind outflow and what scaling laws relate small-scale impulsive or dissipative release events to major flare/eruptive ones?*
  - *In 3D, where and how is plasma heated and are particles accelerated before, during, and after flares and CMEs? How do these processes vary between ions and electrons?*
  - *What are the properties of unresolvable energy release events that drive coronal heating and solar wind outflows and how do these relate to larger, resolvable events?*

Key Challenges:

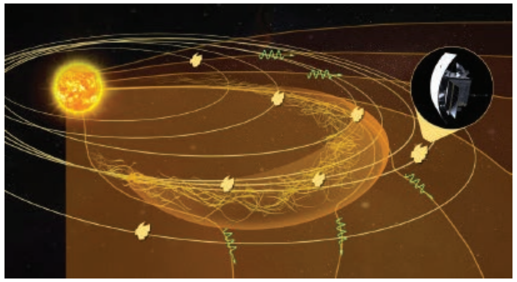
- Adaptation of Gamma-ray Spectroscopic Imager from Balloon Experiment to Space Mission
- Design Definition and Technical Maturation of the Lyman-alpha Hanle Coronagraph
- Hard X-ray Instrument Resolution Improvement Over State of the Art
- Solar Exclusion Zone for High Rate Laser Communications at L1

Technical Risk Rating is Medium

FIGURE G-7 Mission overview for the Multipoint Comprehensive Eruptive Mission (MCEM) concept.
SOURCE: Created by The Aerospace Corporation.

Heliospheric Dynamics Transient Constellation (HDTC)

Overview:



HDTC Heliocentric Constellation (7 spacecraft)

Scientific Objectives:

- Determine how Interplanetary Coronal Mass Ejections (ICMEs) and other geo-effective structures propagate, deflect, and distort as they propagate from the Sun to 1 AU
- Determine how Solar Energetic Particles (SEPs) propagate and diffuse in the inner heliosphere

Key Features:

- Orbiter
  - ***Payload (8 core instruments):*** *Dual Fluxgate Magnetometers (MAG), Solar Wind Electrons (SWE), Solar Wind Composition (SWC), Suprathermal Particles (SP), Low Energy Ions/Electrons (LEIE), High Energy Ions/Electrons (HEIE), Radio Waves (RW), Faraday Cup*
  - ***Flight System:*** *3-5-year life spacecraft, X-band communications, hydrazine propulsion system, 3-axis stabilized, powered by 2 x 2 m^2 solar array wings and 24 Ah Li Ion battery, sun shield for thermal protection*
- Launch: Vulcan VC2S, nominal launch year: 2031
- Mission Design: Ballistic trajectory to Venus with VGA to establish dispersed in 0.4 to 0.9 AU heliocentric orbits, C3 = 5.7 - 6.8 km^2/s^2

Key Challenges:

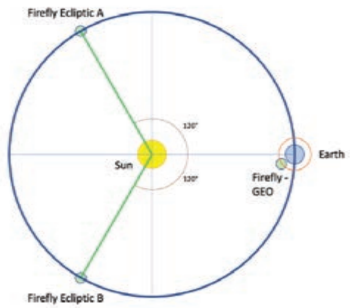
- System thermal environment at 0.4 AU perihelion
- Development of spacecraft solar array for 0.4 AU operation
- Autonomous fault protection for safe recovery of spacecraft
- Low launch mass margin depending on vehicle and launch opportunity

Technical Risk Rating is Medium

FIGURE G-8 Mission overview for the Heliospheric Dynamics Transient Constellation (HDTC) mission concept.
SOURCES: Composed by The Aerospace Corporation; HDTC Heliocentric Constellation image from Szabo et al. (2022), https://doi.org/10.3847/25c2cfeb.7fb78e78. CC BY 4.0.

Ecliptic Heliospheric Constellation (ECH) Mission

EHC:



EHC Constellation (3 satellites)

Key Features:

- EHC Ecliptic (A and B)
  - ***Payload (8 instruments):*** *Doppler Vector Magnetograph (DVM), EUV Imager/Solar Irradiance (EUVI/SI), White Light Coronagraph (WLC), Heliospheric Imager (HI), Fluxgate Magnetometer (FGM), Faraday Cup (FC), Solar Wind Composition (SPICES), Solar Energetic Particle Suite (SEPS)*
  - ***Flight System:*** *10 year lifetime, X-Band and Ka-Band communications, 3-axis stabilized, deployed solar array and 55 Ah Li Ion battery, hydrazine monoprop*
- EHC GEO
  - ***Payload (4 instruments):*** *Doppler Vector Magnetograph (DVM), EUV Imager/Solar Irradiance (EUVI/SI), White Light Coronagraph (WLC), Soft X-ray Spectrometer (SXS)*
  - ***Flight System:*** *10 year lifetime, X-Band and Ka-Band communications, 3-axis stabilized, deployed solar array and 36 Ah Li Ion battery, N2H4/N2O4 biprop*
- Launch: Ecliptic: Falcon 9 launch with C3 = -1.7 km2/s2, GEO: Falcon 9 to GTO at 28.5 deg inc
- Mission Design/Constellation: Ecliptic A: Leading Earth by +120 deg, Ecliptic B: Trailing Earth by -120 deg, GEO: 35,786 km at 28.5 deg inclination

Scientific Objectives:

- Science Goal: To understand the global structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona as it creates the heliosphere.
- Science Objectives:
  - *Understand how surface and subsurface flows and toroidal magnetic field instabilities produce the cyclic dynamo, the root cause of solar activity*
  - *Understand solar magnetic eruptions and the role of large-scale magnetic field connections in triggering eruptions*
  - *Understand the 360 deg view of global sources and transport of energetic particles through the inner heliosphere*

Key Challenges:

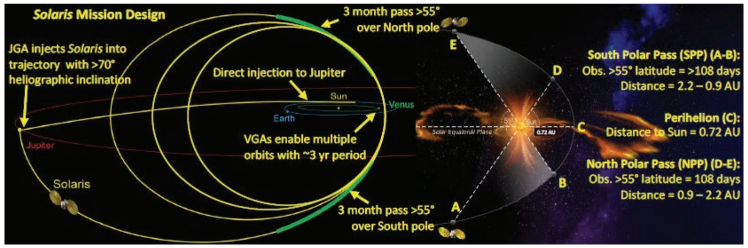
- Development of common spacecraft hardware and software that is qualified for different mission environments
- Some instruments adapted from CubeSat concepts for longer duration mission

Technical Risk Rating is Medium-Low

FIGURE G-9 Mission overview for Ecliptic Heliospheric Constellation (EHC) mission concept.
SOURCE: Created by The Aerospace Corporation.

Solar Polar Orbiter (SPO) Mission

SPO:



SPO Mission Design

Key Features:

- Orbiter
  - ***Payload (8 instruments):*** *Compact Doppler Magnetograph (CDM), EUV Imager (S-EUVI), White Light Coronagraph (S-COR), "boomless" Magnetometer (MAG), Ion Electron Spectrometer (IES), Ion Mass Spectrometer (FIPS), Heliospheric Imager (HI), Energetic Particle Suite (EPS) including Electron Proton Telescope (EPT), High Energy Telescope (HET), and Suprathermal Ion Spectrograph (SIS)*
  - ***Flight System:*** *13.5-year life spacecraft, X-band and Ka-band communications, hydrazine propulsion system, radiation shielded avionics, 3-axis stabilized, powered by 2 x Ultraflex 2kW (1 AU) solar array wings and 70 Ah Li Ion battery*
- Launch: Vulcan VC6S + STAR 27H, nominal launch year: 2030
- Mission Design: Heliocentric escape trajectory, C3 = 104 km^2/s^2 with Jupiter Gravity Assist (JGA), and repeated Venus Gravity Assists (VGAs) resulting in ~ 3 year heliocentric orbit with heliographic inclination > 70 deg

Scientific Objectives:

- To understand how polar magnetic fields and flows reveal the Sun's global dynamics and the mechanisms that underlie the solar dynamo, which ultimately shape the solar activity cycle
- To determine how high-latitude coronal magnetic fields connect the Sun and heliosphere throughout the Solar Cycle
- To determine the role of transient dynamics in structuring the solar wind throughout the Solar Cycle
- Advance space weather research through the first polar magnetograms over multiple solar rotations and simultaneous, 360 deg longitudinal views of coronal structure, variability, and CMEs

Key Challenges:

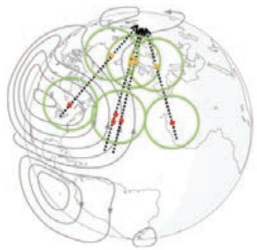
- Ultraflex solar array mechanical reliability under mission loads
- Impacts to flight system from range of environments from Venus to Jupiter
- Reduced Solar Polar Pass duration for some trajectory options
- Verification of system magnetic noise identification for boomless magnetometer
- Limitations of available solar power at Jupiter for critical flyby operations

Technical Risk Rating is Medium

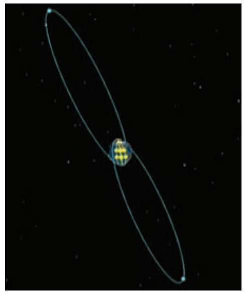
FIGURE G-10 Mission overview for the Solar Polar Orbiter (SPO) mission concept.
SOURCES: Composed by The Aerospace Corporation; SPO Mission image from Hassler et al. (2023), https://doi.org/10.3847/25c2cfeb.408d006f. CC BY 4.0.

Interhemispheric Circuit (I-Circuit) Mission

I-Circuit:



LEO Constellation (10 satellites)



HEO Constellation (2 satellites)

Key Features:

- LEO Orbiters (10 satellites)
  - ***Payload (7 instruments):*** *Global Ultraviolet Imager 2nd Gen (GUVI+), Terahertz Limb Sounder (TLS), Microwave Electrojet Magnetogram (MEM) Sensor, Magnetometer (MAG), Ion Velocity Meter (IVM), Electron Spectrometer (E-Spect), Electric Field Sensor (E-Field)*
  - ***Flight System:*** *30-month lifetime, S-Band & Ka-Band communications, 3-axis stabilized,3.5 m^2 solar array and 11 Ah Li Ion battery, prop for orbit phasing and maintenance*
- HEO Orbiters (2 satellites)
  - ***Payload (2 instruments):*** *Far Ultraviolet Imager (FUV), Electron Spectrometer (E-Spect)*
  - ***Flight System:*** *32-month lifetime small satellite, X-Band communications, 3-axis stabilized, 2 m^2 solar array and 68 Ah Li Ion battery, hybrid prop system for orbit phasing and maintenance*
- Launch: LEO: Falcon 9 (1 launch, 6 satellites), Minotaur IV or similar (2 launches, 2 satellites each), HEO: Vulcan VC0S with STAR 30BP for each of 2 satellites to boost apogee
- Mission Design/Constellation: LEO: 600 km circular orbit at 97 deg inclination, HEO: 600 km x 12 Re at 116.6 deg, Molniya-like "frozen" orbits with argument of perigee space 180 deg apart

Scientific Objectives:

- Determine the system-level effects – energy, momentum, and electrodynamic consequences – of energetic particle precipitation in electrically coupled conjugate hemispheres
  - *Partially addresses ITM goal area: Boundary physics, layers, transport*
    - Establish the pathways by which mass, momentum, and energy are transported and transformed throughout and across ITM boundaries
  - *Also addresses ITM goal area: Cross-scale coupling*
    - Determine how internal ITM processes transform energy and momentum between different spatial and temporal scales
  - *Also addresses ITM goal area: Relative significance of different physical processes for system behavior*
    - Quantify the relative significant of competing physical processes that govern the ITM state

Key Challenges:

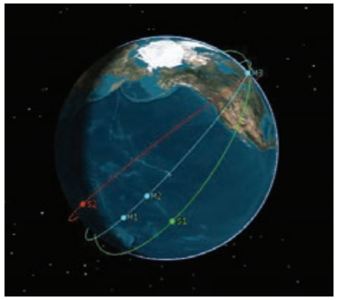
- LEO satellite payload compatibility for seven diverse instruments on a small satellite
- LEO satellite power limitations imposed by spacecraft volume and payload configuration
- Timely deployment of constellation in unique orbit configuration

Technical Risk Rating is Medium-Low

FIGURE G-11 Mission overview for Interhemispheric Circuit (I-Circuit) mission concept.
SOURCE: Created by The Aerospace Corporation.

Buoyancy Restoring-force Atmospheric-wave Vertical-propagation Observatory (BRAVO)

Overview:



BRAVO Constellation (5 satellites)

Scientific Objectives:

- Science Goal: Discover gravity waves' influence on the ionosphere-thermosphere system.
- Science Objectives:
  - *Quantify the spatiotemporal dependence of lower atmosphere gravity wave momentum/energy flux incident upon the I-T*
  - *Determine the evolution of gravity wave influences on the lower/middle thermosphere*
  - *Connect gravity wave influences in the lower/middle thermosphere to ionospheric impacts*

Key Features:

- BRAVO M1 (~ 800 kg class vehicle)
  - ***Payload (3 instruments):** Near IR-band Airglow Camera (NIRCAM), Nadir-Oriented Sodium D2 Resonance LIDAR, GNSS Radio Occultation (GRO)*
  - ***Flight System:** 2.5 year lifetime, S-Band and X-Band communications, 3-axis stabilized,2 kW deployed solar array and 45 Ah Li Ion battery, hydrazine monoprop, based on Thales ELiTeBus*
- BRAVO M2, M3, S1, S2 (~ 300 kg class vehicles)
  - ***M2/M3 Payload (3 instruments):** Near IR-band Airglow Camera (NIRCAM), Terahertz Limb Sounder (TLS), GNSS Radio Occultation (GRO)*
  - ***S1/S2 Payload (3 instruments):** Far UV Imager (FUVI), Terahertz Limb Sounder (TLS), GNSS Radio Occultation (GRO)*
  - ***Flight System:** 2.5 year lifetime, S-Band communications (additional X-Band transmitter for M2/M3), 3-axis stabilized,800 W deployed solar array and 30 Ah Li Ion battery, hydrazine monoprop*
- Launch: Vulcan VC0S to 500 km x 1200 km, 50 deg inclination drift orbit.
- Mission Design/Constellation: 500 km circular orbit at 50 deg inclination, three orbit planes with nodes spaced 20 deg apart

Key Challenges:

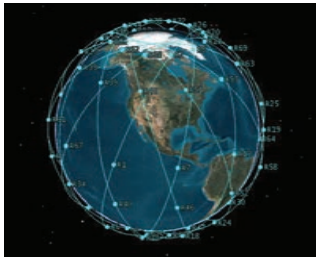
- Challenging LIDAR pointing control requirements on M1
- Updated structural launch interface for M1

Technical Risk Rating is Medium-Low

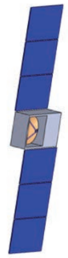
FIGURE G-12 Mission overview for Buoyancy Restoring-Force Atmospheric-Wave Vertical-Propagation Observatory (BRAVO) mission concept.
SOURCE: Created by The Aerospace Corporation.

Resolve Mission

Resolve:



Resolve Constellation (72 satellites)



Resolve 6U CubeSat

Key Features:

- Orbiter
  - ***Payload (1 instrument):*** *Terahertz Limb Sounder (TLS), 4U volume (4000 cm³) for instrument*
  - ***Flight System:*** *3.5-year life 6U CubeSat, S-Band communications, 3-axis stabilized with nano star tracker and GNSS receiver card, powered by multiple 6U solar panels and 9 Ah Li Ion battery, 2U volume (2000 cm³) for spacecraft bus*
- Launch: Electron launch vehicle with Photon kick stage and Terran/Tyvak Nanosatellite Launch Adapter System (NLAS) dispensers, nominal launch year: 2030
  - *6 launches with 12 satellites per launch vehicle*
- Mission Design/Constellation: 500 – 700 km orbit at > 74 deg inclination, 6 satellites per plane, 12 planes total

Scientific Objectives:

- Resolve critical questions about the pathway for energy and momentum transport from the lower atmosphere to the middle and upper atmosphere:
  - *How does lower atmospheric forcing of the upper atmosphere, on horizontal scales greater than ~1000 km, vary on day and hour timescales?*
  - *Under what conditions does lower atmosphere forcing dominate the upper atmospheric dynamics and energy budget?*
  - *To what extent can lower atmosphere forcing explain the observed variability in the ionosphere?*
  - *What are the detailed nonlinear interactions between mean flow, tides, and planetary waves that combine to produce the observed variations, and what are the mechanisms which mediate this coupling?*
  - *How are mean flow, tides, and planetary wave evolution and propagation modified by changes in magnetospheric and solar energy inputs?*

Key Challenges:

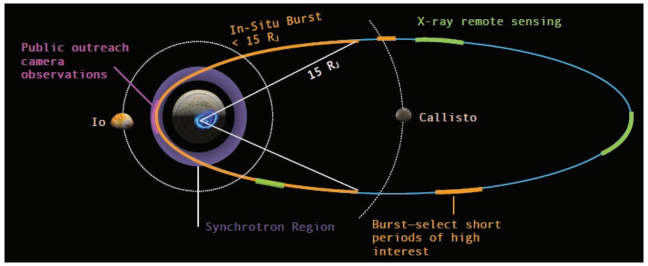
- Accommodating required power for mission within 6U CubeSat constraints
- Capacity for production of 72 TLS instruments and 6U CubeSats
- Fitting system within launch vehicle mass and volume constraints
- Timely constellation deployment for 72 satellites in 12 orbit planes with no on-board satellite propulsion

Technical Risk Rating is Medium

FIGURE G-13 Mission overview for Resolve mission concept.
SOURCE: Created by The Aerospace Corporation.

COMPASS at Jupiter (COMPASS)

Overview:



COMPASS Concept of Operations at Jupiter

Key Features:

- Orbiter
  - ***Payload (10 instrument types):*** *Thermal Plasma Detector x 2 (TPD), Suprathermal Plasma Detector (SPD), Energetic Particle Detector (EPD), Relativistic Particle Detector (RPD), Ultra-relativistic Particle Detector (UPD), Fluxgate Magnetometer x 2 (FGM), Search Coil Magnetometer (SCM), Electric Field Waves (EFW), X-Ray Imager (XRI), and Education/Public Outreach Camera (EPOC)*
  - ***Flight System:*** *7.5-year life spacecraft, X-band communications, hydrazine propulsion system, radiation shielded avionics and instrumentation, spin stabilized, powered by 72 m^2 roll out solar array wings and 42 Ah Li Ion battery*
- Launch: Falcon Heavy Expendable, nominal launch year: 2030
- Mission Design: DV-EGA trajectory to Jupiter, C3 = 52 km^2/s^2 with two orbital phases at Jupiter (200 Rj x 5 Rj with 45 deg inclination and 45 Rj x 1.02 Rj at 15 deg inclination) as well as a transition phase in between

Scientific Objectives:

- Science Goal: Understand how particle origins, acceleration, and loss process compete across a multi-dimensional parameter space that includes space, time, energy, composition, and charge state.
- Particle Origins:
  - *Discover how moon and ring material in the Jovian space environment contribute to the radiation belts*
  - *Reveal the additional particle sources of the Jovian radiation belts*
- Acceleration:
  - *Discover how Jupiter accelerates charged particles to such exceptionally high energies*
  - *Reveal the additional particle sources of the Jovian radiation belts*
- Loss:
  - *Reveal the loss processes of energetic charged particles in Jupiter's magnetosphere and resulting X-ray emissions*

Key Challenges:

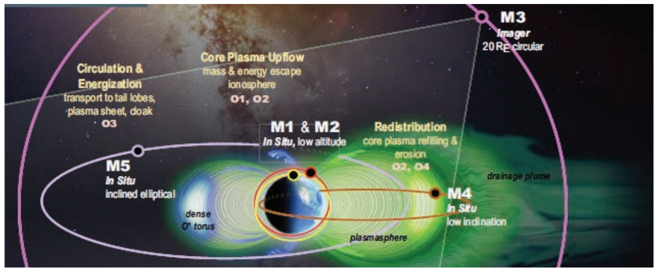
- Large Roll Out Solar Array Development for Usage at Jupiter
- Low Power Margin at End of Mission
- Impact of Radiation Environment at Jupiter
- Low Allowances for System Mass Growth

Technical Risk Rating is Medium

FIGURE G-14 Mission overview for the Comprehensive Observations of Magnetospheric Particle Acceleration, Sources, and Sinks (COMPASS) at Jupiter mission concept.
SOURCE: Created by The Aerospace Corporation.

SOURCE Mission

SOURCE:



SOURCE Constellation

Key Features:

- High Inclination Space Vehicles (M1, M2, M3, M5)
  - ***Payload:*** *M1/M2: CPA, DES, HPCA, Fields Suite (MAG, BWaves, EWaves, ELF), M3: EUV A/B, GPS Rcvr, GCI, ENAS LENA/MENA, M5: TIDE, ASPOC, DES, HPCA, Fields Suite*
  - ***Flight Systems:***
    - **Spinners (M1/M2, M5):** 2 year life spacecraft, S, Ka, or X Band comm up to 200 kbps, LMP-103S propellant, PowerPC avionics, spinning star tracker, body-mounted solar panels
    - **3-axis (M3):** 2 year life spacecraft, Ka Band comm up to 185 kbps, LMP-103S propellant, PowerPC avionics, star tracker, single-axis gimballed solar array
  - *Launch:* ***Vulcan VC4S,*** *350 km x 1500 km @ 90 deg and 4.7 Re x 20 Re*
  - *Orbits (90 deg inc): M1/M2: 350 km x 1500 km, M3: 20 Re circular, M5: 4Re x 15Re*
- GTO Space Vehicle (M4)
  - ***Payload:*** *HOPE, SPB System, Fields Suite*
  - ***Flight System (Spinner, M4):*** *2 year life spacecraft, X Band comm up to 71 kbps, LMP-103S propellant, PowerPC avionics, spinning star tracker, body-mounted solar panels*
  - *Launch:* ***Falcon 9 or Vulcan*** *Rideshare to GTO*
  - *Orbit: Geosynchronous Transfer Orbit*

Scientific Objectives:

- Mission Science Goal: To understand the processes and pathways by which core magnetospheric ions flow from the ionosphere, and are energized and redistributed within and throughout geospace
- SOURCE Science Objectives:
  - *Determine how magnetospheric and solar energy inputs cause outflow of ionospheric plasma into the magnetosphere*
  - *Determine the mechanisms that drive refilling and isotropization of the plasmasphere*
  - *Determine the pathways of core plasma transport and energization through the lobes and tail to help create the plasma sheet, warm plasma cloak, and ring current*
  - *Understand how the plasmasphere is eroded and redistributed during disturbances*

Key Challenges:

- Developing common hardware/software for spacecraft with different instruments and orbits to achieve savings
- Achieving high accuracy attitude determination and control for spinner spacecraft

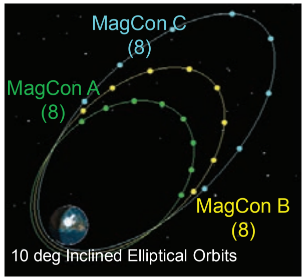
Technical Risk Rating is Medium-Low

SOURCE = Synchronized Observations of Upflow, Redistribution, Circulation, and Energization

FIGURE G-15 Mission overview for the Synchronized Observations of Upflow, Redistribution, Circulation, and Energization (SOURCE) mission concept.
SOURCES: Composed by The Aerospace Corporation; SOURCE Constellation image from Goldstein et al. (2023), https://baas.aas.org/pub/2023n3i132/release/1. CC BY 4.0.

Links Mission

Links:



MagCon Constellation

PARAGON Constellation

Key Features:

- MagCon (24 satellite constellation)
  - ***Payload:*** *Magnetometer (MAG), Solid State Telescope (SST), Electrostatic Analyzer (ESA), Charge/Discharge Sensor (CDS)*
  - ***Flight System:*** *39-month life spacecraft, S-band communications up to 2.5 Mbps, Hydrazine propellant system, microsat avionics, spinning satellite, powered by body-mounted solar panels*
- Launch: **Vulcan VC4S,** injection orbit: 1.1Re x 10.79 Re at 10 deg inc, nominal launch: 2031
- Orbits: A: 1.49Re x 8.24Re, B: 1.29Re x 10.79Re, C: 1.11Re x 15Re at 10 deg inclination
- PARAGON (2 satellite constellation)
  - ***Payload:*** *Energetic Neutral Atom Wide Angle Camera (ENA WAC), Energetic Neutral Atom Narrow Angle Camera (ENA NAC) x 2, Far Ultraviolet Imager (FUV) x 2, Charge/Discharge Sensor (CDS)*
  - ***Flight System:*** *39-month life spacecraft, S-band communications up to 4.5 Mbps, Hydrazine propellant system, smallsat avionics, 3-axis stabilized, powered by deployed solar panels*
- Launch: **Falcon 9,** nominal launch: 2031
- Orbit: 9Re circular at 70-90 deg inclination

Scientific Objectives:

- Discover, quantify, and understand the global impact of mesoscale processes in the flow of mass, momentum, and energy through geospace
- Understand mesoscale energy input at the dayside magenetopause and flanks (e.g., the extent and temporal evolution of magnetopause reconnection)
- Understand the global impact of mesoscale magnetospheric energy flow:
  - How do plasma sheet mesoscale structures transport and energize plasma from the plasma sheet to the inner magnetosphere? Under what conditions and to what extent do they contribute to the buildup of the storm-time ring current?
- Observe the global impact of mesoscale MI coupling:
  - How does the aurora respond to transient mescale plasma sheet structures?

Key Challenges:

- Capacity for building a fleet of 24 MagCon instrument suites and spacecraft may exceed the resources of many potential suppliers
- High tempo early orbit operation of a 24 MagCon satellite constellation in highly elliptical 10 deg inclined orbit without crosslinks and with limited direct communications capability

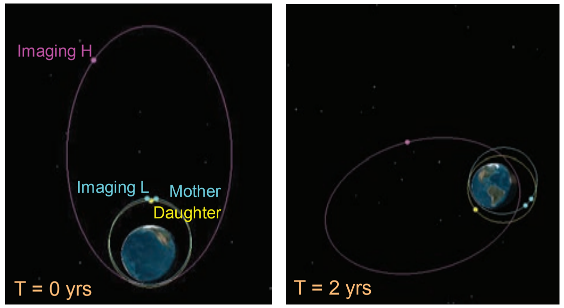
Technical Risk Rating is Medium-Low

PARAGON = Plasma Acceleration, Reconfiguration, and Aurora Geospace Observation Network
MagCon = Magnetospheric Constellation

FIGURE G-16 Mission overview for Links mission concept.
SOURCE: Created by The Aerospace Corporation.

Observatory for Heteroscale Magnetosphere-Ionosphere Coupling

OHMIC:



OHMIC Constellation (4 satellites)

Scientific Objectives:

- Discover how electromagnetic energy is converted to particle energy to power the aurora and ionospheric outflows
  - *Determine how energy conversion and transport vary along the magnetic field*
  - *Determine how ionospheric outflow is mediated by ion heating, convection, and field-aligned transport*
  - *Determine how coupled parallel and perpendicular dynamics regulate energy conversion in discrete aurora*
- Coordinated multi-spacecraft observations intended to overcome the limitations of previous single spacecraft auroral missions to resolve fundamental outstanding questions in auroral physics and magnetosphere-ionosphere (MI) coupling

Key Features:

- Mother and Daughter Satellites
  - ***Payload (2 instrument suites):*** *Auroral Plasma Instrument (API): API/Electrons & API/Ions; Electromagnetic Fields Instrument (EFI): EFI/Fluxgate Magnetometer, EFI/Langmuir Probe, EFI/E-Field (Axial & Spin-Plane), EFI/Electronics Box*
  - ***Flight System:*** *27-month lifetime, S-Band and X-Band communications, spin stabilized, body mounted solar array and 15 Ah Li Ion battery, hydrazine monoprop for orbit adjustment*
- Imaging Satellites (Low and High)
  - ***Payload (1 instruments):*** *UV Optical Imager (UVI)*
  - ***Flight System:*** *27-month lifetime small satellite, S-Band and X-Band communications, 3-axis stabilized, 1.5 m^2 solar array and 15 Ah Li Ion battery, hydrazine monoprop for orbit adjustment*
- Launch: Falcon 9 from Vandenberg AFB: Dispense Mother, Daughter, and Imaging Low at 500 x 5,500 km at 90 deg inclination, with each satellite using on-board propulsion to reach final orbit; use F9 upper stage to boost apogee to 43,800 km and dispense Imaging High
- Mission Design/Constellation: Mother: 500 x 6000 km, Daughter: 1000 x 5500 km, Imaging Low: 500 x 6000 km, Imaging High: 500 x 43,800 km, all at 90 deg inclination

Key Challenges:

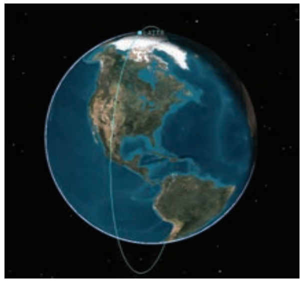
- Developing common designs for Imaging spacecraft with different orbits to achieve savings
- Mother and Daughter spacecraft require attention to magnetic cleanliness

Technical Risk Rating is Medium-Low

FIGURE G-17 Mission overview for the Observatory for Heteroscale Magnetosphere-Ionosphere Coupling (OHMIC) mission concept.
SOURCE: Created by The Aerospace Corporation.

LAITIR: Low Altitude Ionosphere and Thermosphere In-situ Researcher

Overview:



LAITIR Low Perigee Mission

Scientific Objectives:

- Explore the region of the lower thermosphere from 100-200 km and how Joule heating dravies the geospacer environment
  - *Determine how the ionospheric Joule heating is influenced by and influences neutral wind, composition, temperature, and density*
  - *Determine how spatial and temporal variations in density, composition, and temperature of the neutral lower thermosphere (100-200 km) and ionosphere depend on preconditioning and solar activity*
  - *Determine the conditions under which non-Maxwellian processes regulate ion-neutral coupling*

Key Features:

- Orbiter
  - ***Payload (5 instruments):*** *Ion Drift/Velocity Meter (IVM), Winds-Ions-Neutral Composition Suite (WINCS), Vector Electric Fields Investigation (VEFI), Magnetometer (MAG), Electron Spectrometer (ES)*
  - ***Flight System:*** *3-year life spacecraft, S-band communications, hydrazine propulsion system, 3-axis stabilized, powered body mounted 9.5 m^2 cylindrical solar array and 26 Ah Li Ion battery*
- Launch: Minotaur-C (evolved Taurus), nominal launch years: 2030, 2032, 2035
- Mission Design: Launch to 2000 km x 225 km, 85 deg inclined orbit. Conduct Low Perigee Campaigns every 60 days with 45 days at survey perigee = 225 km and 15 days at minimum perigee = 120-150 km. Repeat campaigns for 3 years on each satellite, launching a second satellite at 2.5 years and a third satellite at 5 years (6 month overlap)

Key Challenges:

- Uncertainty in satellite drag at low perigee impacts overall mission/system design
- Impact of low altitude environment on instrument and spacecraft design
- Future availability of launch vehicle suited to this mission
- Strict electromagnetic cleanliness requirements for space vehicle

Technical Risk Rating is Medium

FIGURE G-18 Mission overview for the Low-Altitude Ionosphere and Thermosphere In Situ Researcher (LAITIR) mission concept.
SOURCE: Created by The Aerospace Corporation.

G.3 REFERENCES

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H

Acronyms and Abbreviations

AAAS	American Association for the Advancement of Science
AAS	American Astronomical Society
AC	atmosphere cluster
ACCESS	Advanced Cyberinfrastructure Coordination Ecosystem: Services and Support
ACCESS	Applications of Commercial Constellations for Expanded Science and Space Weather
ACE	Advanced Composition Explorer
ACR	anomalous cosmic ray
ADAS	Atomic Data and Analysis Structure
AE-C	Atmospheric Explorer-C
AE-E	Atmospheric Explorer-E
AFOSR	Air Force Office of Scientific Research
AGS	NSF Division of Atmospheric and Geospace Sciences
AGU	American Geophysical Union
AI	artificial intelligence
AIM	Aeronomy of Ice in the Mesosphere
AIMI	Panel on Atmosphere–Ionosphere–Magnetosphere Interactions
ALMA	Atacama Large Millimeter/submillimeter Array
AMIE	Assimilative Mapping of Ionosphere Electrodynamics
AMISR	Advanced Modular Incoherent Scatter Radar
AMPERE	Active Magnetosphere and Planetary Electrodynamics Response Experiment
AMS	American Meteorological Society
ANSWERS	Advancing National Space Weather Expertise and Research toward Societal Resilience
AO	announcement of opportunity
AO	atomic oxygen
APEX	Astrophysics Probe Explorer
APL	Applied Physics Laboratory
AR	active region
ARMS	Adaptively Refined MHD Solver
ARTEMIS	Acceleration, Reconnection, Turbulence, and Electrodynamics of Moon's Interaction with the Sun

AS	Airspace Systems
ASI	all-sky imager
AST	NSF Division of Astronomical Sciences
ASTRE	Atmosphere–Space Transition Region Explorer
ATI	Advanced Technologies and Instrumentation
AURIC	Atmospheric Ultraviolet Radiance Integrated Code
AWE	Atmospheric Waves Experiment
AWSoM	Alfvén Wave Solar Model
BAPSF	Basic Plasma Science Facility
BARREL	Balloon Array for Radiation-belt Relativistic Electron Losses
BBSO/GST	Big Bear Solar Observatory Goode Solar Telescope
BDD	Burst Detect Dosimeter
BEA	U.S. Bureau of Economic Analysis
BMPL	Bryn Mawr Plasma Laboratory
BRAVO	Buoyancy Restoring-force Atmospheric-wave Vertical-propagation Observatory
CAIG	Collaborations in Artificial Intelligence and Geosciences
CAMI	Civil Aerospace Medical Institute
CARA	Conjunction Assessment and Risk Analysis
CAREER	Faculty Early Career Development Program
CARI	Civil Aviation Research Institute
CARISMA	Canadian Array for Realtime Investigations of Magnetic Activity
CCMC	Community Coordinated Modeling Center
CDM	conjunction data message
CDP	commercial data purchase
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CESM	Community Earth System Model
CGEM	Coronal Global Evolutionary Model
CGMS	Coordination Group for Meteorological Satellites
CGO	Carruthers Geocorona Observatory
CGS	Center for Geospace Storms
ChroMag	Community Synoptic Chromospheric Magnetograph
CIMI	Comprehensive Inner Magnetosphere–Ionosphere
CIP	community input paper
CIR	corotating interaction region
CIRES	Cooperative Institute for Research in Environmental Sciences Climate
CLARO	Coronal Lyman-Alpha Resonance Observatory
CLASP	Chromospheric Layer Spectropolarimeter-2
CLD	Commercial Low Earth Orbit Development
CLEDB	Coronal Line Emission Database
CLPS	Commercial Lunar Payload Services
CMAM	Canadian Middle Atmosphere Model
CME	coronal mass ejection
CMEx	Chromospheric Magnetism Explorer
CMIP	Coupled Model Intercomparison Project
CMOS	complementary metal oxide semiconductor
C/NOFS	Communications/Navigation Outage Forecasting System
CO5BOLD	COnservative COde for the COmputation of COmpressible COnvection in a BOx of L Dimensions with l=2,3

COE	[Space Weather] Centers of Excellence
COFFIES	Consequences of Fields and Flows in the Interior and Exterior of the Sun
Co-I	co-investigator
COMP	Coronal Multi-channel Polarimeter
COMPASS	Comprehensive Observations of Magnetospheric Particle Acceleration, Sources, and Sinks
CORS	Continuously Operating Reference Station
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
COSMO	Coronal Solar Magnetism Observatory
COSPAR	Committee on Space Research
CRIS	Cosmic Ray Isotope Spectrometer
CRISP	CRisp Imaging Spectro-Polarimeter
Cryo-NIRSP	Cryogenic Near-IR Spectro-Polarimeter
CSA	Canadian Space Agency
CSM	Community Science Modeling
CSSWE	Colorado Student Space Weather Experiment
CTIPe	Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics Model
CUSIA	Community for the Unified Study of Interhemispheric Asymmetries
CWDP	Commercial Weather Data Pilot
CXD	Combined X-ray Dosimeter
DA	data assimilation
DASHI	Distributed Arrays of Scientific Heterogeneous Instruments
DASI	Distributed Arrays of Small Instruments
DAVINCI	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging
DE-1	Dynamics Explorer 1
DEIA	diversity, equity, inclusion, and accessibility
DKIST	Daniel K. Inouye Solar Telescope
DL	downlink
DMSP	Defense Meteorological Satellite Program
DMU	drag makeup
DoD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOI	digital object identifier
DOY	day of the year
DRAP	D-Region Absorption Prediction
DRIVE	diversify, realize, integrate, venture, educate
DSC	DRIVE Science Center
DSCOVR	Deep Space Climate Observatory
DSN	Deep Space Network
DST	Dunn Solar Telescope
DTM	Drag Temperature Model
DYNAMIC	Dynamical Neutral Atmosphere–Ionosphere Coupling
ECCCO	EUV CME and Coronal Connectivity Observatory
ECIP	NASA Early Career Research Program
ECLIPSE	Ecosystem for Leading Innovation in Plasma Science and Engineering
EDR	electron diffusion region
E-Field	electric field sensor
EHC	Ecliptic Heliospheric Constellation

EIA	equatorial ionization anomaly
EISCAT	European Incoherent Scatter Scientific Association
ELFIN	Electron Losses and Fields Investigation
EMTF	Empirical Magnetotelluric Transfer Functions
ENA	energetic neutral atom
ENLoTIS	ESA/NASA Lower Thermosphere–Ionosphere Science
ENSO	El Niño–Southern Oscillation
EO	emerging opportunity
EOVSA	Expanded Owens Valley Solar Array
EPB	equatorial plasma bubble
ERC	European Research Council
ERSA	European Radiation Sensors Array
ESA	European Space Agency
EscaPADE	Escape and Plasma Acceleration and Dynamics Explorers
ESDMD	Exploration System Development Mission Directorate
ESP	energetic storm particle
ESPA	external evolvable launch vehicle secondary payload adapter
E-Spect	electron spectrometer
ETR	exobase transition region
EUI	Extreme Ultraviolet Imager
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EUV	extreme ultraviolet
EUVST	Extreme Ultraviolet High-throughput Spectroscopic Telescope
EVE	Extreme ultraviolet Variability Experiment
EZIE	Electrojet Zeeman Imaging Explorer
FA	focus area
FAA	Federal Aviation Administration
FAC	field-aligned current
FAIR	findable, accessible, interoperable, reusable
FAR	False Alarm Ratio
FASR	Frequency-Agile Solar Radiotelescope
FAST	Fast Auroral Snapshot
FDSS	Faculty Development in geoSpace Science
FINESST	Future Investigators in NASA Earth and Space Science and Technology
FIP	first ionization potential
FIREBIRD	Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics
FLARE	Facility for Laboratory Reconnection Experiments
FLIP	field line interhemispheric plasma
FST	focused science topic
FTE	full-time equivalent
FUV	far ultraviolet
FY	fiscal year
GAO	U.S. Government Accountability Office
GBO	ground-based observatory
GBT	Green Bank Telescope
GC	Geospace Cluster
GCR	galactic cosmic ray
GDC	Geospace Dynamics Constellation

GDP	gross domestic product
GEANT	Geometry and Tracking
GEC	Geospace Electrodynamics Connections Explorer
GEM	Geospace Environment Modeling
GEMINI	Geospace Environment Model of Ion-Neutral Interactions
GEO	geostationary orbit
GEO	[NSF] Directorate for Geosciences
GFM	Geoelectric Field Model
GFS	Global Forecast System
GGS	global geospace science
GIC	geomagnetically induced current
GLE	ground-level enhancement
GloTEC	Global Total Electron Content
GLOW	Global Airglow Model
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GOLD	Global-Scale Observations of the Limb and Disk
GONG	Global Oscillation Network Group
GPS	global positioning system
GQ	guiding question
GRFP	NSF Graduate Research Fellowships Program
GRIS	GREGOR Infrared Spectrograph
GSI	gas–surface interactions
GSRP	Graduate Student Researchers Program
GTO	geosynchronous transfer orbit
GUVI	Global Ultraviolet Imager
HAARP	High-frequency Active Auroral Research Program
HALO	[Gateway] Habitat and Logistics Outpost
HAMMONIA	Hamburg Model of the Neutral and Ionized Atmosphere
HAO	High Altitude Observatory
H-ARD	Heliophysics Artificial Intelligence/Machine Learning Ready Data
HARP	Heliophysics Audified: Resonances in Plasma
HASDM	High Accuracy Satellite Drag Model
HDEE	Heliophysics Data Environment Enhancement
HDR	Harnessing the Data Revolution
HDTC	Heliospheric Dynamics Transient Constellation
HE	hydrostatic equilibrium
HEC	high-end computing
HEEO	highly elliptical Earth orbit
HeLEX	Heliophysics Large Explorer
HEO	highly elliptical orbit
HEPPA	High Energy Particle Precipitation
HERMES	Heliophysics Environmental and Radiation Measurement Experiment Suite
HESTO	Heliophysics Strategic Technology Office
HF	high frequency
H-FORT	Heliophysics Flight Opportunities for Research and Technology
H-FOS	Heliophysics Flight Opportunity Studies
HGI	Heliophysics Guest Investigator
HGIO	Heliophysics Guest Investigator—Open

HISFM	Heliophysics Internal Scientist Funding Model
HITL	human-in-the-loop
H-LCAS	Heliophysics Low Cost Access to Space
HMI	Helioseismic and Magnetic Imager
HP	heliopause
HPAC	Heliophysics Advisory Committee
HPC	high-performance computing
HPD	[NASA] Heliophysics Division
HSL	HelioSystems Laboratory
HSO	Heliophysics Systems Observatory
HSR	Heliophysics Supporting Research
HTIDeS	Heliophysics Technology and Instrument Development for Science
HTM	Heliophysics Theory, Modeling, and Simulation
HW	Habitable World
HWM	Horizontal Wind Model
HXR	hard X-ray
HYPERS	Hybrid Particle Event-Resolved Simulator
HZETRN	High Charge (Z) and Energy Transport
IAA	interagency agreement
I-ALiRT	Interstellar Mapping and Acceleration Probe Active Link for Real-Time
IBEX	Interstellar Boundary Explorer
IBIS	Interferometric Bidimensional Spectropolarimeter
IC	infrastructure cluster
ICAO	International Civil Aviation Organization
I-Circuit	Interhemispheric Circuit
ICME	interplanetary coronal mass ejection
ICON	Ionospheric Connection Explorer
IDS	interdisciplinary scientists
IGERT	Integrative Graduate Education and Research Traineeship
IHA	interhemispheric asymmetries
ILWS	International Living With a Star
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMAP	Interstellar Mapping and Acceleration Probe
IMF	interplanetary magnetic field
INMS	ion and neutral mass spectrometer
IPCC	Intergovernmental Panel on Climate Change
IPM	interplanetary medium
IRB	independent review board
IRI	International Reference Ionosphere
IRIS	Interface Region Imaging Spectrograph
IS	incoherent scatter (radar)
ISEP	Solar Energetic Particle Warning System
ISMF	interstellar magnetic field
ISRIM	Incoherent Scatter Radar Model
ISRO	Indian Space Research Organization
ISS	International Space Station
ISTPNext	Next International Solar Terrestrial Program Next-Generation
ISWAT	Space Weather Action Teams
I-T	ionosphere–thermosphere

ITM	ionosphere–thermosphere–mesosphere
IVM	Ion Velocity Meter
JAXA	Japan Aerospace Exploration Agency
JHUAPL	Johns Hopkins University Applied Physics Laboratory
JMA	Japan Meteorological Agency
JPSS	Joint Polar Satellite System
JUICE	Jupiter Icy Moons Explorer
JWST	James Webb Space Telescope
KASA	Korean Aerospace Administration
K-Cor	Coronal Solar Magnetism Observatory K-Coronagraph
KDP	key decision point
KH	Kelvin-Helmholtz
KMA	Korea Meteorological Agency
KOMP	Korean Multi-Purpose Satellite
KoSO	Kodaikanal Solar Observatory
LAITIR	Low Altitude Ionosphere and Thermosphere In Situ Researcher
LANL	Los Alamos National Laboratory
LAPD	Large Plasma Device
LASCO	Large Angle and Spectrometric Coronagraph
LAT	Fermi Large Area Telescope
LBH	Lyman-Birge-Hopfield
LEO	low Earth orbit
LEXI	Lunar Environment Heliospheric X-ray Imager
LIC	local interstellar cloud
LiDAR	light detection and ranging
LISM	local interstellar medium
LISN	Low-Latitude Ionospheric Sensor Network
LOFAR	low-frequency array
LOMPE	European Local Mapping of Polar Ionospheric Electrodynamics
LOS	line-of-sight
LRG	longer-range goal
LTRX	Line-Tied Reconnection Experiment
LWS	Living With a Star
M2M	Moon to Mars
MACAWS	Multicenter Airborne Coherent Atmospheric Wind Sensor
MACH	Magnetic fields, Atmospheres, and Connection to Habitability
MAE	mean absolute error
MAG	magnetometer
MAG	Panel on the Physics of Magnetospheres
MAGE	Multiscale Atmosphere–Geospace Environment Model
MAGPIE	Mega Ampere Generator for Plasma Implosion Experiments
MAS	Magnetohydrodynamic Algorithm outside a Sphere
MAVEN	Mars Atmosphere and Volatile Evolution
MCEM	Multipoint Comprehensive Eruptive Mission
MEM	microwave electrojet magnetogram
MEO	medium Earth Orbit
MERRA	Modern-Era Retrospective Analysis for Research and Applications

MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, Version 2
MESSENGER	Mercury Surface, Space Environment, Geochemistry, and Ranging
MetOp	Meteorological Operational
MFR	magnetic flux rope
MHD	magnetohydrodynamic
M-I	magnetosphere–ionosphere
MICA	Magnetosphere–Ionosphere Coupling in the Alfvén Resonator
MIDEX	Medium-Class Explorer
MIGHTI	Michelson Interferometer for Global High-Resolution Thermospheric Imaging
MIMO	multiple-in–multiple-out
MinXSS	Miniature X-ray Solar Spectrometer
MIO	Magnetosphere–Ionosphere Observatory
M-I-T	magnetosphere–ionosphere–thermosphere
ML	machine learning
MLSO	Mauna Loa Solar Observatory
MLT	magnetic local time
MLT	mesosphere and lower thermosphere
MMS	Magnetospheric Multiscale Mission
MO	Mission of Opportunity
MOA	memorandum of agreement
MOU	memorandum of understanding
MPS	NSF Directorate for Mathematical and Physical Sciences
MREFC	Major Research Equipment and Facilities Construction
MRI	Major Research Infrastructure
MRX	Magnetic Reconnection Experiment
MSIS	Mass Spectrometer Incoherent Scatter Radar
MSL	Mars Science Laboratory
MSRI	Mid-Scale Research Infrastructure
MT	magnetotelluric
MURaM	Max Planck Institute for Solar System Research/University of Chicago Radiative MHD
MUSE	Multi-Slit Solar Explorer
MWA	Murchison Widefield Array
NAS	NASA Advanced Supercomputing Division
NASA	National Aeronautics and Space Administration
NAVGEM-HA	Navy Global Environmental Model-High Altitude
NAVy	Global Environmental Model NAVGEM
NCAR	National Center for Atmospheric Research
NEON	Near Earth Orbit Network
NERC	Natural Environmental Research Council
NESDIS	National Environmental Satellite, Data, and Information Service
NetCDF	Network Common Data Form
ngGONG	Next Generation Global Oscillations Network Group
NIF	National Ignition Facility
NIRAC	near-infrared airglow camera
NMDB	Neutron Monitor DataBase
NOAA	National Oceanic and Atmospheric Administration
NO_x	nitrogen oxides
NRAO	National Radio Astronomy Observatory
NRCan	Natural Resources Canada

NRL	Naval Research Laboratory
NRLMSIS	Naval Research Laboratory Mass Spectrometer Incoherent Scatter Radar
NRT	near real time
NSB	National Science Board
NSF	National Science Foundation
NSN	Near Space Network
NSO	National Solar Observatory
NSPIRES	NASA Solicitation and Proposal Integrated Review and Evaluation System
NSPO	[Taiwan] National Space Organization
NSS	National Security Space
NuSTAR	Nuclear Spectroscopic Telescope Array
NWS	National Weather Service
O2R	operations-to-research
OASIS	Operations and Science Instrument Support
ONR	Office of Naval Research
OpenGGCM	Open Geospace General Circulation Model
OPP	NSF Office of Polar Programs
OSE	observing system experiment
OSS	open source science
OSSE	observing system simulation experiment
OTHR	Over-the-Horizon Radar
OVATION	Oval Variation, Assessment, Tracking, Intensity, and Online
OVRO-LWA	Owens Valley Radion Observatory's Long Wavelength Array
PCI	Polar Cap Indices
PFISR	Poker Flat Incoherent Scatter Radar
PFSS	potential field source surface
PHASMA	phase space mapping
PHY	NSF Division of Physics
PI	principal investigator
PIC	particle-in-cell
PIXIE	Polar Ionospheric X-ray Imaging Experiment
PNA	prefer not to answer
PNT	Positioning, Navigation, and Timing
POD	Precise Orbit Determination
POES	Polar Operational Environmental Satellites
POS	plane of the sky
PPPL	Princeton Plasma Physics Laboratory
PROBA	Project for Onboard Autonomy
PROBA2	Project for Onboard Autonomy 2
PROSWIFT	Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act
PSG	priority science goal
PSP	Parker Solar Probe
PUI	pickup ion
PUNCH	Polarimeter to Unify the Corona and Heliosphere
QPP	quasi-periodic pulsation
R&A	research and analysis

R2O	research to operations
R2O2R	research to operations to research
RAAN	right ascension of the ascending node
RAD	Radiation Assessment Detector
RADYN	Radiation Hydrodynamics Code
RAMENS	Radiative Magnetohydrodynamic Extensive Numerical Solver
REFM	Relativistic Electron Forecast Model
REU	Research Experiences for Undergraduates
RF	radio frequency
RFB	Radio Frequency Beacon
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
RISR	Resolute Bay Incoherent Scatter Radar
RISR-C	Resolute Bay Incoherent Scatter Radar—Canada
RISR-N	Resolute Bay Incoherent Scatter Radar—North
RL	readiness level
ROSES	Research Opportunities in Space and Earth Science
RSTN	Radio Solar Telescope Network
SAA	South Atlantic Anomaly
SABER	Sounding of the Atmosphere Using Broadband Emission Radiometry
SAGA	Scintillation Auroral Global Positioning System Array
SAID	subauroral ion drift
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SAPS	subauroral polarization stream
SAR	stable auroral red
SCaN	Space Communication and Navigation Program
SCATHA	Spacecraft Charging At High Altitudes
SCIFER	Sounding of the Cleft Ion Fountain Energization Region
SDAC	Solar Data Analysis Center
SDO	Solar Dynamics Observatory
SEAESRT	Spacecraft Environmental Anomalies Expert System—Real Time
SED	storm-enhanced density
SEE	Solar EUV Experiment
SEON	Solar Electro-Optical Network
SEP	solar energetic particle
SGPS	Solar and Galactic Proton Sensor
SHIELD	Solar wind with Hydrogen Ion charge Exchange and Large-Scale Dynamics
SHINE	Solar, Heliospheric, and Interplanetary Environment
SHP	Panel on the Physics of the Sun and Heliosphere
SIGMA	Satellite-beacon Ionospheric-scintillation Global Model of the upper Atmosphere
SIR	stream interaction region
SLAMS	Short Large-Amplitude Magnetic Structures
SLS	space launch system
SMD	Science Mission Directorate
SMEX	Small Explorer
SMILE	Solar wind Magnetosphere Ionosphere Link Explorer
SML	SuperMAG Lower Index
SOARS	[NSF] Significant Opportunities in Atmospheric Research and Science
SOHO	Solar and Heliospheric Observatory
SOL	Space weather Observations at L1
SOLIS	Synoptic Optical Long-Term Investigations of the Sun

SoloHI	Solar Orbiter Heliospheric Imager
SOMD	Space Operations Mission Directorate
SoP	state of the profession
SORTIE	Scintillation Observations and Response of the Ionosphere to Electrodynamics
SOSS	Supplements for Open-Source Science
SOT	Solar Optical Telescope
SOURCE	Synchronized Observations of Upflow, Redistribution, Circulation, and Energization
SPA	Space Physics and Aeronomy Section of the American Geophysical Union
SPD	Solar Physics Division of the American Astronomical Society
SPD-3	Policy Directive 3
SPDF	Space Physics Data Facility
SPO	Solar Polar Orbiter
SPORT	Scintillation Prediction Observations Research Task
SPRING	Solar Physics Research Integrated Network Group
SPS	Spectral Plasma Solver
SPSC	Space Physics Simulation Chamber
SRAG	Space Radiation Analysis Group
SRS-3	Solar Radiation Scale-3
SSA	space situational awareness
SSA	strategic science area
SST	Swedish Solar Tower
SSW	sudden stratospheric warming
SSX	Swarthmore Spheromak Experiment
STC	science and technology center
STEAM	science, technology, engineering, arts, and mathematics
STEM	science, technology, engineering, and mathematics
STEMM	science, technology, engineering, mathematics, and medicine
STEREO	Solar Terrestrial Relations Observatory
STEVE	strong thermal emission velocity enhancement
STIX	Spectrometer Telescope for Imaging X-rays
STMD	Space Technology Mission Directorate
STP	Solar Terrestrial Probe
SunRISE	Sun Radio Interferometer Space Experiment
SuperDARN	Super Dual Auroral Radar Network
SUVI	Solar Ultraviolet Imager
SWAG	Space Weather Advisory Group
SWaP	size, weight, and power
SWAP	Sun Watcher with Active Pixels and Image Processing
SWARM-EX	Space Weather Atmospheric Reconfigurable Multiscale Experiment
SWFO-L1	Space Weather Follow On-Lagrange 1
SWMF	[University of Michigan] Space Weather Modeling Framework
SWMI	Panel on Solar Wind–Magnetosphere Interactions
SWO	[NOAA] Office of Space Weather Observations
SWORM	Space Operations, Research, and Mitigation
SWP	[NASA] Space Weather Program
SWPC	[NOAA] Space Weather Prediction Center
SWPT	Space Weather Prediction Testbed
SWQU	Space Weather with Quantified Uncertainties
SWSA	Panel on Space Weather Science and Applications

SWSAP	National Space Weather Strategy and Action Plan
SWUG	Space Weather Underground
SXR	soft X-ray
T&M	theory and modeling
TAD	traveling atmospheric disturbance
TDO	technology demonstration option
TDRSS	Tracking and Data Relay Satellite System
TEC	total electron content
TESS	Transiting Exoplanet Survey Satellite
TGRS	Tri-GNSS Radio-occultation System
THEMIS	Time History of Events and Macroscale Interactions During Substorms
TID	traveling ionospheric disturbance
TIE-GCM	Thermosphere–Ionosphere–Electrodynamics General Circulation Model
TIMED	Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics
TLS	terahertz limb sounder
TOPS	Transform to Open Science Program
TR	transition region
TR&T	targeted research and technology
TRACE	technical, risk, and cost evaluation
TRACERS	Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites
TraCSS	Traffic Coordination System for Space
TREX	Terrestrial Reconnection Experiment
TRICE-2	Twin Rocket Investigation of Cusp Electrodynamics 2
TRL	technology readiness level
TS	termination shock
TWINS	Two Wide-Angle Imaging Neutral-Atom Spectrometers
UCAR	University Corporation for Atmospheric Research
UCoMP	Upgraded Coronal Multi-channel Polarimeter
UFKW	ultra-fast Kelvin wave
ULF	ultra-low frequency
UNOOSA	UN Office for Outer Space Affairs
URM	underrepresented minority
USAP	U.S. Antarctic Program
USGS	U.S. Geological Survey
USSF	U.S. Space Force
UV	ultraviolet
UVI	Ultraviolet Imager Instrument
VADR	Venture Class Acquisition of Dedicated and Rideshare
VCLS	Venture Class Launch Service
VERB	Versatile Electron Radiation Belt
VERITAS	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy
VIIRS	Visible Infrared Imaging Radiometer Suite
VISIONS	Visualizing Ion Outflow via Neutral Atom Sensing
ViSP	Visible Spectro-Polarimeter
VLA	Karl G. Jansky Very Large Array
VLF	very low frequency
VLISM	very local interstellar medium
VSO	Virtual Solar Observatory

WACCM-X	Whole Atmosphere Community Climate Model—eXtended
WAM-IPE	Whole Atmosphere Model—Ionosphere Plasmasphere Electrodynamics
WAVE	Wave-Induced Atmospheric Variability Enterprise
WDC-SILSO	World Data Center—Sunspot Index and Long-Term Solar
WHPI	Whole Heliosphere and Planetary Interactions
WINCS	Winds–Ion–Neutral–Composition Suite
WISPR	Wide-Field Imager for Parker Solar Probe
WMO	World Meteorological Organization
WPI	wave–particle interaction
WSA	Wang-Sheeley-Arge
XRP	Exoplanets Research Program
YIP	Young Investigator Program

I

Committee and Panel Biographical Information

STEERING COMMITTEE

STEPHEN A. FUSELIER, *Co-Chair*, is executive director of the Space Science Directorate at Southwest Research Institute and previously served as a researcher and senior manager at Lockheed Martin Advanced Technology Center. Dr. Fuselier is the deputy principal investigator (PI) and sensor lead on the Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS), co-investigator (Co-I) on the Interstellar Mapping and Acceleration Probe (IMAP), Co-I and sensor lead on the Interstellar Boundary Explorer (IBEX) mission, Co-I and lead for the Hot Plasma Composition Experiment (HPCA) on the Magnetospheric Multiscale Mission, Co-I and lead for the ion instruments on the Twin Rocket Investigation of Cusp Electrodynamics 2 (TRICE-2), Co-I on the Imager for Magnetopause to Aurora Global Exploration (IMAGE), and lead U.S. Co-I on the Rosetta orbiter spectrometer for ion and neutral analysis (ROSINA). Dr. Fuselier is the author or co-author of more than 500 scientific publications, a fellow of the American Geophysical Union (AGU), the 1995 recipient of the AGU James B. Macelwane Award, and the 2016 recipient of the European Geosciences Union Hannes Alfvén Award and is a member of the National Academy of Sciences. Dr. Fuselier received his PhD in space plasma physics from the University of Iowa. He has previously served as a member of the Committee for the Review of Progress Toward Implementing the Decadal Survey—Solar and Space Physics: A Science for a Technological Society.

ROBYN M. MILLAN, *Co-Chair*, is the Margaret Anne and Edward Leede ’49 Distinguished Professor of Physics and Astronomy at Dartmouth College. Dr. Millan’s research focus is energetic particle processes and explosive energy release in planetary magnetospheres. She was PI for the Balloon Array for Radiation-Belt Relativistic Electron Losses (BARREL) and is currently the PI for the Relativistic Electron Atmospheric Loss (REAL) CubeSat, which will make high time resolution measurements of electron pitch angle and energy distributions in low Earth orbit to characterize the mechanisms responsible for scattering radiation belt electrons. Dr. Millan has worked to promote the development of small satellites for space science, has served as AGU Space Physics and Aeronomy secretary, and has chaired committees at Dartmouth College and the National Academies, and at national and international levels. She is a recipient of the National Aeronautics and Space Administration’s (NASA’s) Exceptional Public Achievement Medal and Dartmouth’s John M. Manley Huntington Award for Newly Promoted Faculty. She received her PhD in physics at the University of California, Berkeley. Dr. Millan has previously served as co-chair of the Committee for the Review of Progress Toward Implementing the Decadal Survey—

Solar and Space Physics: A Science for a Technological Society. She recently served on the advisory committee for the National Science Foundation (NSF) Geosciences Directorate but stepped down when she accepted the co-chair position for this decadal survey.

FRANCES BAGENAL is a senior research scientist at the Laboratory for Space and Atmospheric Physics of the University of Colorado Boulder and leads its Magnetospheres of the Outer Planets Group. Prior to that, Dr. Bagenal was a professor of astrophysical and planetary sciences at the same institution. Her research interests focus primarily on planetary physics of gas giants—specifically, understanding the magnetospheres by combining data analysis and theoretical models. Dr. Bagenal has been co-investigator on several highly successful NASA missions, including Voyager, Galileo, New Horizons, and Juno. She is the recipient of the James Van Allen Lecture Award from the AGU and the Boulder Faculty Assembly's Excellence in Research Award. She is involved in the American Astronomical Society's Planetary Science Workforce Survey, and is a member of the National Academy of Sciences. In National Academies' work, Dr. Bagenal co-chaired the Committee on Increasing Diversity and Inclusion in the Leadership of Competed Space Missions, was a member of the 2003 Solar and Space Physics Survey Panel on Education and Society, and was a member of the Panel on Giant Planets Systems of the Planetary Science and Astrobiology Decadal Survey 2023–2032. Dr. Bagenal received a PhD in Earth and planetary sciences from the Massachusetts Institute of Technology (MIT).

TIMOTHY S. BASTIAN is an astronomer with the National Radio Astronomy Observatory (NRAO) and an adjunct faculty member in the Astronomy Department at the University of Virginia. Formerly, Dr. Bastian served as head of the NRAO Office of Science and Academic Affairs, assistant director and head of Observatory Science Operations, and assistant director and head of Science Support and Research. His research interests include solar and stellar radiophysics, planetary/exoplanetary radio emission, radio propagation phenomena as probes of the solar wind, the physics of flares and coronal mass ejections, the physics of the chromosphere, and ground- and space-based interferometry. Dr. Bastian is currently a Co-I on the NASA SunRISE mission and the NSF Expanded Owens Valley Solar Array and leads the Atacama Large Millimeter/submillimeter Array (ALMA) Solar Development Group. Previous National Academies' service includes the 2003 decadal survey Panel on Solar and Heliospheric Physics, the Committee on Solar and Space Physics, the Committee for the Review of Progress Toward Implementing the Decadal Survey—Solar and Space Physics: A Science for a Technological Society, and chair of the Committee on Assessment of the NSF's 2015 Geospace Portfolio Review. Dr. Bastian received a PhD in astrophysics from the University of Colorado.

SARBANI BASU is the William K. Lanman Jr. Professor of Astronomy at Yale University. Dr. Basu's research interests include the study of the Sun and other stars using data on stellar oscillations (star quakes), and in studying the variations in the Sun over timescales that are of societal relevance. To this end, she uses solar oscillation data to examine changes that take place deep inside the Sun over periods of years and decades. Dr. Basu is a Co-I on the Helioseismic and Magnetic Imager of NASA's Solar Dynamics Observatory. She is the recipient of the George Ellery Hale Prize of the Solar Physics Division of the American Astronomical Society and the M.K. Vainu Bappu Gold Medal of the Astronomical Society of India. Dr. Basu is a fellow of the American Association for the Advancement of Science. She was chair of the Panel on Stars, Sun, and Stellar Populations for the Astro2020 decadal survey. Dr. Basu received a PhD in physics from the Tata Institute of Fundamental Research.

RICHARD DOE is an instrument subject matter expert at Cornell Technical Services. Dr. Doe's previous experience includes work as a senior research physicist at SRI International, research associate at Boston University, senior RF engineer at Lockheed Engineering and Management Services, EMI test engineer at Texas Instruments, and sonar technician at UT Applied Research Laboratory. His research interests include radar, UV photometer, imaging, and RF beacon instruments; high-latitude plasma turbulence and structuring; ionospheric and space weather remote sensing; and CubeSat mission design, development, and operations. Dr. Doe has served as a panel reviewer for the NSF Division of Atmospheric and Geospace Sciences, the NASA Heliophysics Division, and the NASA Earth Science Division, and as a member of the NSF Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) Science Steering Committee. Dr. Doe received a PhD in astronomy and astrophysics from Boston University.

EILEEN DUKES is the sole proprietor of Interplanetary Horizons. Ms. Dukes was formerly chief technology officer of Vestigo Aerospace. Her experience and technical expertise includes decades of leading the planning and operation of challenging deep space missions, attitude determination and control subsystems (ADCS), and the development and implementation of ADCS flight software algorithms. Prior to joining Vestigo Aerospace, Dukes led mission operations for planetary applications at the Lockheed Martin Corporation and was responsible for the ADCS implementations of the first atmospheric aerobraking at Venus and Mars. Ms. Dukes is a recipient of the NASA Public Service Medal. She received a BS in aeronautics and astronautics from MIT.

SCOTT L. ENGLAND is an associate professor at Virginia Polytechnic Institute and State University (Virginia Tech) in the Aerospace and Ocean Engineering Department. Dr. England's research involves studying coupling of energy and momentum between different regions of the atmosphere via atmospheric waves. He spent 12 years at the Space Sciences Laboratory at the University of California, Berkeley, studying the interaction between atmospheric waves and charged particles in the near-Earth space environment. At Virginia Tech, his research focuses on using remote sensing and in situ instruments to study the upper atmosphere and space environment around Earth and Mars. Dr. England is the project scientist for the NASA Ionospheric Connection Explorer (ICON) spacecraft, co-investigator on the NASA Global-Scale Observations of the Limb and Disk (GOLD) mission, co-investigator on the Emirate Mars Mission (EMM), participating scientist on the NASA Mars Atmosphere and Volatile Evolution (MAVEN) mission to Mars, and co-investigator for an instrument on NASA's Geospace Dynamics Constellation (GDC). Dr. England was the recipient of a 2016 NASA RHG Exceptional Achievement for Science award for MAVEN and a 2020 NASA group achievement award for ICON. He received a PhD for radio and plasma physics at the University of Leicester, UK, and was a member of the Committee for the Review of Progress Toward Implementing the Decadal Survey—Solar and Space Physics: A Science for a Technological Society.

ALLISON N. JAYNES is an associate professor of physics and astronomy at the University of Iowa, researching space and plasma physics. Her primary research interests include pulsating auroras, radiation belts, and the connection between the two. Dr. Jaynes has been co-investigator on NASA's Van Allen Probes missions and on the Voyager mission, the NASA-funded CubeSats GTOSat and AEPEX, and a NASA-funded sounding rocket mission, LAMP. She served on the Nomination Task Force within AGU's Space Physics and Aeronomy (SPA) section assembled to increase the diversity of honors and awards winners at AGU. Dr. Jaynes currently serves on the Heliophysics Subcommittee of the NASA Advisory Council but has agreed to step down when appointed. She served on the National Academies' Committee on Increasing Diversity and Inclusion in the Leadership of Competed Space Missions. Dr. Jaynes received a PhD in physics from the University of New Hampshire.

DANA WARFIELD LONGCOPE is a professor and head of the Department of Physics at Montana State University, Bozeman. Dr. Longcope's research interests include the study of the basic physics of magnetic fields in ionized plasmas and the application of these concepts to magnetic fields on the Sun. Dr. Longcope has studied the storage and release of magnetic energy in the Sun's corona through a process known as reconnection. He is a recipient of a Faculty Early Career Development grant from the National Science Foundation, a Presidential Early Career Award for Science and Engineering, the Karen Harvey Prize from the Solar Physics Division of the American Astronomical Society, and the Arktowski Medal from the National Academy of Sciences. Dr. Longcope received a PhD in applied physics from Cornell University.

VIACHESLAV G. MERKIN is a principal professional staff scientist at Johns Hopkins University Applied Physics Laboratory (JHU/APL). Dr. Merkin is also the supervisor of the Theory and Modeling Section at JHU/APL's Space Plasma Physics group and currently holds the position of an affiliate scientist at the National Center for Atmospheric Research High Altitude Observatory. Dr. Merkin's research interests include numerical modeling of space plasma environments such as planetary magnetospheres and the inner heliosphere. He is the director of the NASA Diversify, Realize, Integrate, Venture, Educate (DRIVE) Science Center for Geospace Storms, which was recently selected for Phase II (2022–2027). Dr. Merkin received a PhD in physics from the University of Maryland at College Park.

DANIEL MÜLLER is a solar physicist and Solar Orbiter Project Scientist at the European Space Technology and Research Centre of the European Space Agency (ESA). Dr. Müller previously served as ESA's deputy project scientist for the ESA/NASA Solar and Heliospheric Observatory (SOHO) mission at NASA's Goddard Space Flight Center (GSFC). Prior to joining ESA, Dr. Müller held a Marie Curie postdoctoral fellowship at the Institute of Theoretical Astrophysics at the University of Oslo, Norway, and worked as a research scientist and research assistant at the Kiepenheuer Institute for Solar Physics in Freiburg, Germany. His research interests and activities include solar physics, helioinformatics, solar spectropolarimetry, and the numerical modeling of the solar corona. Dr. Müller is currently collaborating with researchers at NASA GSFC, the Leibniz Institute for Solar Physics (formerly the Kiepenheuer Institute for Solar Physics), the Institute of Theoretical Astrophysics at the University of Oslo, Norway, the Royal Observatory of Belgium, the Universidad de Almeria, Spain, and the ESTEC-ESAC Heliophysics Group in Noordwijk, The Netherlands. He received his PhD in physics from the Albert-Ludwigs-Universitaet Freiburg, Germany.

TERRANCE G. ONSAGER is a physicist with the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center. Dr. Onsager's research includes solar wind–magnetosphere coupling, modeling the signatures of magnetic reconnection at Earth's magnetopause and in the magnetotail, and the dynamics of the electron radiation belts. It also includes coordinating the capabilities and priorities of international space weather organizations to improve global space weather services and working to bridge the gap between research and operations. Dr. Onsager has served as the director of the International Space Environment Service, as co-chair of the World Meteorological Organization Inter-Programme Coordination Team on Space Weather, and as a member of the Space Weather Expert Team for the United Nations Committee on the Peaceful Use of Outer Space Working Group on the Long-Term Sustainability of Outer Space. He received a PhD in physics from the University of Washington.

TAI D. PHAN is a senior fellow at the University of California, Berkeley, in the Space Sciences Laboratory. Dr. Phan's research interests include solar wind interaction with Earth's magnetosphere and the magnetic reconnection process in space. He is a co-investigator of the NASA Time History of Events and Macroscale Interactions During Substorms (THEMIS) mission and is a science co-investigator of the FIELDS instrument on the Solar Probe Plus mission. Dr. Phan led an interdisciplinary science team of the NASA Magnetospheric Multiscale mission. He is a fellow of the AGU, and he previously served on the National Academies' Committee on Solar and Space Physics and the 2013 decadal survey Panel on Solar Wind–Magnetosphere Interactions. Dr. Phan received a PhD in engineering from Dartmouth College.

TUIJA PULKKINEN is chair and George R. Carignan Collegiate Professor at the University of Michigan in Ann Arbor in the Department of Climate and Space Sciences and Engineering. Previously, Dr. Pulkinnen served as professor, vice president, and dean of the School of Electrical Engineering at Aalto University, Espoo, Finland. Prior to Aalto University, she was a scientist, unit head, and research professor at the Finnish Meteorological Institute in Helsinki, Finland. Dr. Pulkkinen's research interests cover solar wind–magnetosphere–ionosphere coupling, energy and plasma transport from the solar wind into the magnetosphere–ionosphere system, and auroral region electrodynamics and its coupling to the magnetosphere. Dr. Pulkkinen has been awarded the European Geosciences Union Julius Bartels Medal, the AGU fellowship, and the James B. Macelwane Medal. She is a member of the Academia Europaea, the Royal Astronomical Society, and the Finnish Academy of Sciences and Letters. Dr. Pulkkinen is the co-chair of the National Academies' Committee on Solar and Space Physics. She received a PhD in theoretical physics from the University of Helsinki.

LIYING QIAN is a project scientist III at the High Altitude Observatory (HAO), National Center for Atmospheric Research (NCAR). Dr. Qian studies space weather impact and space climate change in the thermosphere and ionosphere (TI) system, coupling of the TI system with the lower atmosphere and the magnetosphere, and ion and neutral coupling within the TI system. Dr. Qian has extensive experience in upper atmosphere and whole atmosphere general circulation modeling, and data analysis of the TI system from space- and ground-based measurements. Dr. Qian is a recipient of HAO's Walter O. Roberts scientific and technical advancement award, the University Corporation for Atmospheric Research scientific and technical advancement award, and the NCAR/HAO John W. Firor publication award, and the NASA group achievement award to TIMED/SEE science team. Dr. Qian received a PhD in atmospheric science from Pennsylvania State University.

MARILIA SAMARA is a research astrophysicist in the Geospace Physics Laboratory of the Heliophysics Science Division at NASA GSFC. Previously, Dr. Samara was a principal scientist at Southwest Research Institute in San Antonio, Texas. Dr. Samara studies space plasmas with an emphasis on ionospheric electrodynamics and ionosphere–magnetosphere coupling using both suborbital and orbital particle and wave instruments. She has a particular passion for space hardware and studying small-scale auroral structure and dynamics using common volume in situ and ground-based measurements. Dr. Samara was principal investigator of the Ground-to-Rocket Electrodynamics–Electrons Correlative Experiment (GREECE) sounding rocket and is co-investigator on numerous sounding rockets. GREECE demonstrated that multispectral ground imaging of the aurora alone can be used to infer the two-dimensional electron characteristics of the precipitating electrons creating the aurora. Other current projects include serving as the deputy principal investigator of the Electron Electrostatic Analyzer (EEA) instrument of the Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES) science payload for the Lunar Gateway, the Dione CubeSat, and the Comprehensive Auroral Precipitation Experiment (CAPE) on the Geospace Dynamics Constellation (GDC), all in development. Dr. Samara received a PhD in physics and astronomy from Dartmouth College.

JOSHUA SEMETER is a professor of electrical and computer engineering at Boston University (BU) and director of the BU Center for Space Physics. Dr. Semeter's previous appointments include senior research engineer at SRI International, postdoctoral fellow at the Max Planck Institute for Extraterrestrial Physics, and control systems engineer at Pratt & Whitney Aircraft. Dr. Semeter's lab seeks to understand interactions between the atmosphere, ionosphere, and magnetosphere that underlay space weather. His research employs combinations of physics-based modeling, radio and optical remote sensing, satellite observations, and physics-based data fusion. Current research interests include high-speed flow channels in the ionosphere, small-scale plasma irregularities and their effects on radio wave propagation, ionospheric signatures of magnetic reconnection, and applications of data science and artificial intelligence to distributed observations of the geospace environment. Dr. Semeter has also served on the advisory committee to the NSF Geoscience Directorate (AC-GEO), and as chair of the NSF program on Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR). He was a recipient of the NSF Faculty Early Career Development (CAREER) award and has received multiple awards for teaching at Boston University. Dr. Semeter has served on the National Academies' Committee on Solar and Space Physics, the 2013 Panel on Atmosphere–Ionosphere–Magnetosphere Interactions, and the Committee for the Review of Progress Toward Implementing the Decadal Survey—Solar and Space Physics: A Science for a Technological Society. He received a PhD in electrical engineering from Boston University.

ENDAWOKE YIZENGAW is a senior scientist at the Aerospace Corporation. His research interests include the complexities of ionospheric electrodynamics using multiple instrument techniques from ground and space. Dr. Yizengaw developed the African Meridian B-Field Education and Research (AMBER) network of magnetometer instruments in more than 10 countries and has played a vital role in the expansion of space science education and research in developing countries. He participates in the International Space Weather Initiative (ISWI), was active in the International Heliophysical Year (IHY) program, and has performed scientific outreach programs for young scientists in the United States and developing nations. Dr. Yizengaw is currently on the Scientific Steering Committee of the NSF Coupling, Energetics, and Dynamics of Atmospheric Regions Program. He has co-convened conferences in Africa, including an AGU Chapman Conference and a number of programs of the International Space Weather Initiative and the International Heliophysical Year. Dr. Yizengaw was awarded the AGU's Joanne Simpson Medal. He received a PhD in space science from La Trobe University, Australia.

GARY P. ZANK is the director of the Center for Space Plasma and Aeronomic Research (CSPAR), University of Alabama Board of Trustees Trustee Professor, Aerojet/Rocketdyne Chair in Space Science, an Eminent Scholar and distinguished professor, and chair of the Department of Space Science at the University of Alabama in Huntsville. Dr. Zank's research interests extend across space physics, plasma astrophysics, plasma physics, and the interaction of the solar wind with the partially ionized interstellar medium. He was named the University of Alabama Board of Trustees Trustee Professor, the first and only University of Alabama System faculty member to achieve this position. Dr. Zank is a recipient of the Axford Medal, the highest honor given by the Asia Oceania Geosciences Society (AOGS). He is a fellow of the AGU, the American Physical Society, and the American Association for the Advancement of Science. Dr. Zank is also an AOGS honorary member and was chosen by the International Space Science Institute as a Johannes Geiss Fellow. He received a PhD in applied mathematics from the University of Natal in South Africa.

Study Staff

ARTHUR CHARO, *Study Director*, has been a senior program officer with the National Academies' SSB since 1995. He has directed studies resulting in some 41 reports, notably the inaugural "decadal surveys" in solar and space physics (2002) and Earth science and applications from space (2007). He also served as the study director for the second Earth Science decadal (2018) and the second (2012) and third (2024, in preparation) decadal surveys in solar and space physics. Dr. Charo received his PhD in experimental atomic and molecular physics in 1981 from Duke University and was a postdoctoral fellow in chemical physics at Harvard University from 1982 to 1985. He then pursued his interests in national security and arms control as a fellow from 1985 to 1988 at Harvard University's Center for Science and International Affairs. From 1988 to 1995, he worked as a senior analyst and study director in the International Security and Space Program at the Congressional Office of Technology Assessment. In addition to contributing to SSB reports, he is the author of research papers in the field of molecular spectroscopy, reports on arms control and space policy, and the monograph "Continental Air Defense: A Neglected Dimension of Strategic Defense" (University Press of America, 1990). Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985–1987) and a Harvard-Sloan Foundation Fellowship (1987–1988). He was a 1988–1989 American Association for the Advancement of Science (AAAS) Congressional Science Fellow, sponsored by the American Institute of Physics.

ABIGAIL SHEFFER, *Study Director*, is a senior program officer with the SSB. Dr. Sheffer has been the staff officer and study director on a variety of activities such as the Decadal Survey on Astronomy and Astrophysics (Astro2020), the Committee on Solar and Space Physics, Open Source Software Policy Options for NASA Earth and Space Sciences, Strategic Investments in Instrumentation and Facilities for Extraterrestrial Sample Curation and Analysis, and Achieving Science with CubeSats: Thinking Inside the Box, among others. In 2009, Dr. Sheffer came to the National Academies as a Christine Mirzayan Science and Technology Policy Graduate Fellow with the SSB. She earned her PhD in planetary science from the University of Arizona.

COL. GEORGE COYLE, USAF (retired), has had a lifelong dual-track career in science and technology (S&T) and the U.S. Air Force, spanning government, corporate business, the finance industry, and academia over several decades. These two tracks have synergistically leveraged his background in operations, research, technology development, technology transition, acquisition, business development, the finance industry, and manufacturing. Dr. Coyle brought this experience to the National Academies as a senior program officer. Over the past 9 years, he has led consensus studies, workshops and workshop series, roundtables, and meetings of experts for the Air Force Studies Board (AFSB), the Intelligence Community Studies Board (ICSB), the Health and Medicine Division (HMD), and most recently as Responsible Staff Officer (RSO) for the Magnetosphere Panel of the Solar and Space Physics Decadal for NASA. Dr. Coyle received his PhD in geochemistry at the University of Maryland studying solar wind irradiation of lunar surface mineralogy.

CHRISTOPHER J. JONES joined the National Academies in 2016 and is a senior program officer. His recent work has primarily focused on physics and astronomy, including decadal studies and field assessments across physics subfields such as plasma physics; a national strategic plan for fusion energy; and shepherding panels for the astronomy and heliophysics decadal studies. Prior to his current posting at the National Academies, Dr. Jones had the honor of serving as a congressional fellow in the Senate for energy topics, a White House fellow working on material science and water quality issues, and a Fulbright grantee assessing water quality in Budapest, Hungary. Dr. Jones received his PhD from Rice University and BS from Florida State University, both in chemistry.

ARUL MOZHI is a senior program officer and associate director of the ASEB and the SSB at the National Academies. Since 1999, Dr. Mozhi has been directing projects in the areas of defense and broader science and technology carried out by numerous committees of ASEB, SSB, the Laboratory Assessments Board, the Army Research Laboratory Technical Assessment Board, the Naval Studies Board, and the National Materials and Manufacturing Board. Prior to joining the National Academies, Dr. Mozhi held technical and management positions in systems engineering and applied materials research and development (R&D) at several small- and mid-size high-tech R&D and consulting companies in the Washington, DC, and Boston areas—UTRON, Roy F. Weston, and Marko Materials. He received his MS and PhD (the latter in 1986) in materials engineering from the Ohio State University and then served as a postdoctoral research associate there for 2 years. He received his BTech in metallurgical engineering from the Indian Institute of Technology, Kanpur, in 1982.

MIA BROWN joined the SSB as a research associate in 2016. Ms. Brown comes to the SSB with experience in both the civil and military space sectors and has primarily focused on policies surrounding U.S. space programs in the international sector. Some of these organizations include NASA's Office of International and Interagency Relations, Arianespace, the United Nations Office for Disarmament Affairs (Austria), and the U.S. Department of State. From 2014 to 2015, Ms. Brown was the managing editor of the *International Affairs Review*. She received her MA in international space policy from the Space Policy Institute at the Elliott School of International Affairs at George Washington University. Prior to entering the Space Policy Institute, Ms. Brown received her MA in historical studies from the University of Maryland, Baltimore County, where she concentrated in the history of science, technology, and medicine and defended a thesis on the development of the 1967 Outer Space Treaty.

MEGAN CHAMBERLAIN joined the SSB and the ASEB as a senior program assistant in 2019. Ms. Chamberlain began her career at the National Academies in 2007 working for the Transportation Research Board in the Cooperative Research Programs. She has assisted with meeting facilitation and administrative support of hundreds of research projects over the course of her career. Ms. Chamberlain attended the University of the District of Columbia and majored in psychology.

COLLEEN N. HARTMAN joined the National Academies in 2018, as the director for both the Space Studies Board (SSB) and the Aeronautics and Space Engineering Board (ASEB). After beginning her government career as a presidential management intern under Ronald Reagan, Dr. Hartman worked on Capitol Hill for House Science and Technology Committee Chair Don Fuqua, as a senior engineer building spacecraft at NASA GSFC, and as a senior policy analyst at the White House. She has served as the Planetary Division director, deputy associate administrator, and acting associate administrator at NASA's Science Mission Directorate; as the deputy assistant administrator at NOAA; and as the deputy center director and director of science and exploration at NASA GSFC. Dr. Hartman has built and launched scientific balloon payloads, overseen the development of hardware for a variety of Earth-observing spacecraft, and served as NASA program manager for dozens of missions, the most successful of which was the Cosmic Background Explorer (COBE). Data from the COBE spacecraft gained two NASA-sponsored scientists the Nobel Prize in physics in 2006. Dr. Hartman also played a pivotal role in developing innovative approaches to powering space probes destined for the solar system's farthest reaches. While at NASA Headquarters, she spearheaded the selection process for the New Horizons probe to Pluto. She helped gain administration and congressional approval for an entirely new class of funded missions that are competitively selected, called "New Frontiers," to explore the planets, asteroids, and comets in the solar system. She has several master's degrees and a PhD in physics. Dr. Hartman has received numerous awards, including two prestigious Presidential Rank Awards.

PANEL ON THE PHYSICS OF THE SUN AND HELIOSPHERE

DANIEL B. REISENFELD, *Co-Chair*, is a senior scientist and team leader in the Space Science and Applications group at Los Alamos National Laboratory. Prior to that, Dr. Reisenfeld was a professor of physics and astronomy and department chair at the University of Montana. He has broad space science research interests, including the evolution and composition of the solar wind, the physics of the outer heliosphere, and the magnetospheres of the outer planets. Dr. Reisenfeld is a deputy instrument lead on the Interstellar Mapping and Acceleration Probe (IMAP) and a deputy instrument lead on the Interstellar Boundary Explorer (IBEX). He was also a co-instrument lead for the Cassini Plasma Spectrometer (CAPS) aboard the Cassini mission to Saturn, and a Co-I on the Genesis Discovery mission. Dr. Reisenfeld has chaired numerous NASA and LANL-DOE space science proposal review panels. He received a PhD in astronomy from Harvard University.

SABRINA L. SAVAGE, *Co-Chair*, is a mission and project scientist at NASA Marshall Space Flight Center (MSFC). Dr. Savage has been serving since 2014 as the U.S. project scientist overseeing the U.S. participation for the Hinode mission and has actively participated in the Heliophysics Living with a Star Program since 2018. Her research pursuits center around solar flares using high-energy instrumentation to understand the mechanics behind how the magnetic field rapidly releases enormous amounts of energy into our solar neighborhood. Dr. Savage also participates in the development of new solar instrumentation for testing on sounding rockets, including the upcoming first-ever solar flare campaign set to occur in 2024. In addition, she has been participating in preparing for coordination of a broad swath of research on the (lunar) Gateway activities, which will provide unprecedented opportunities for deep space exploration payloads across disciplines. Dr. Savage received a PhD in physics from Montana State University.

GIANNA CAUZZI is an associate scientist at the National Solar Observatory (NSO). Since joining NSO in 2017, Dr. Cauzzi has been responsible for community outreach and education related to the Daniel K. Inouye Solar Telescope (DKIST) science, as coordinator of the DKIST Critical Science Plan Workshops and of the DKIST Data Workshops series. She is currently the chair of the Science Review Committee for evaluation of observing proposals submitted to DKIST. Dr. Cauzzi has extensive expertise on magnetic and dynamical properties of small-scale structures in the lower solar atmosphere, including wave dynamics and heating, and the physics of flares and eruptive phenomena. Her research has an observational focus, both for what concerns instrumentation—in particular, imaging spectro-polarimeters based on Fabry-Perot interferometers—and for the use of high-resolution solar observations and data analysis. Dr. Cauzzi has led multiple international observing campaigns involving both space- and ground-based facilities and has organized related scientific gatherings discussing the resulting science. She received a PhD in astronomy from the University of Florence, Italy.

BIN CHEN is an associate professor of physics at the New Jersey Institute of Technology. Prior to that, Dr. Chen was an astrophysicist at the Harvard-Smithsonian Center for Astrophysics. His research interests have centered on the study of solar flares and coronal mass ejections, which include developing novel radio observing techniques and utilizing multiwavelength observations to study the explosive energy release processes. Dr. Chen is currently a co-principal investigator for the Expanded Owens Valley Solar Array project. He was a recipient of the NSF Faculty Early Career Development Award and the NASA Living-with-a-star Jack Eddy Fellowship. Dr. Chen served as a committee member of the Solar Physics Division of the American Astronomical Society. He received a PhD in astronomy from the University of Virginia.

MAUSUMI DIKPATI is a senior scientist with the National Center for Atmospheric Research's (NCAR) High Altitude Observatory. Dr. Dikpati's primary research area has been global magnetohydrodynamics (MHD) of the Sun, to simulate solar variability on timescales from a few days to several months, up to a decade; with recent focus on solar MHD Rossby waves, their implications for pre-solar-storm activity patterns, and for predicting the "stormy seasons" of space weather. Dr. Dikpati has been one of the pioneers in the application of modern data assimilation methods to solar models. She won the John Firor HAO Outstanding Publication award for her physics-based solar cycle prediction paper. Dr. Dikpati's research on the extended minimum at the end of solar cycle 23 was recognized as one of the top 100 science discoveries in 2011 by *Discover Magazine*. She received a PhD from the Indian Institute of Science, Bangalore.

JOE GIACALONE is a professor at the Lunar and Planetary Laboratory at the University of Arizona. Dr. Giacalone's research interests include understanding the origin, acceleration, and propagation of cosmic rays and other charged-particle species in the magnetic fields of space. This includes developing physics-based theoretical and computational models that are used to interpret in situ spacecraft observations. Dr. Giacalone is currently involved in the following spacecraft: Solar Orbiter; Interstellar Mapping and Acceleration Probe (IMAP); Parker Solar Probe, Integrated Science Investigation of the Sun Instrument; and Advanced Composition Explorer. He received a PhD in physics from the University of Kansas.

LINDSAY GLESENER is an associate professor in the School of Physics and Astronomy at the University of Minnesota. Prior to joining the University of Minnesota, Dr. Glesener was an assistant researcher at the University of California, Berkeley. She works in high-energy studies of the Sun and other stars, especially studying electron acceleration and the heating of coronal plasma. Her expertise is in observation and instrumentation. Dr. Glesener received an NSF CAREER Award. She received a PhD in physics from the University of California, Berkeley.

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SUSAN T. LEPRI is a professor at the University of Michigan. Dr. Lepri's research involves solar wind heavy ions and development of heavy ion mass spectrometers for in situ observations in the heliosphere. In addition to conducting research and maximizing the scientific return of data sets from operational spacecraft, including ACE and WIND, she also develops space-based ion mass spectrometers, working with a team of scientists and engineers at the University of Michigan. Dr. Lepri received the University of Michigan Willie Hobbs Moore Award: Claudia Joan Alexander Trailblazer Award. She received a PhD in atmospheric and space sciences from the University of Michigan.

ANDRÉS MUÑOZ-JARAMILLO is a senior research scientist at the Southwest Research Institute in Boulder, Colorado, and a visiting scholar at the National Center for Atmospheric Research's High Altitude Observatory (HAO) and the National Solar Observatory (NSO). His research interests include understanding and predicting the solar magnetic cycle and its impact on solar variability, space climate, and terrestrial climate change. Dr. Muñoz-Jaramillo uses advanced techniques of deep learning, data mining and analysis, and data visualization to accelerate discovery from large volumes of data. Dr. Muñoz-Jaramillo was awarded a Jack Eddy Postdoctoral Fellowship and the AGU's Fred L. Scarf Award. He received a PhD in physics from Montana State University.

SUSAN E. POPE is director of the Space Instrumentation Department at the Southwest Research Institute in San Antonio, Texas. She has broad experience in space instrument mechanical design, systems engineering, and management. Dr. Pope has built a career from the foundation of mechanical engineering, gaining specific knowledge of the particular complexities of designing and building hardware for spaceflight. This segued into systems engineering, where she managed the requirements behind the engineering, from single instruments to entire missions. This culminated as project manager for the Interstellar Mapping and Acceleration Probe (IMAP) payload, where her technical expertise allows communication across all mission systems to manage cost and schedule knowledgeably. Dr. Pope has also performed various roles on multiple NASA and ESA missions. She received an MS in engineering management from the University of Texas, Austin.

BRIAN E. WOOD is a research physicist with the Space Sciences Division of the Naval Research Laboratory. Prior to joining the Naval Research Laboratory, Dr. Wood was a research associate at the University of Colorado Boulder and an astrophysicist at the Harvard-Smithsonian Center for Astrophysics. His research interests involve observational studies of the Sun and Sun-like stars. Dr. Wood is also an expert on solar wind and coronal mass ejection (CME) data analysis and has developed techniques for reconstructing the 3D morphology and kinematics of CMEs based on coronagraph and heliospheric imager observations, utilizing data from the Solar and Heliospheric Observatory (SOHO), Parker Solar Probe (PSP), and Solar Terrestrial Relations Observatory (STEREO). His astrophysical work mostly involves chromospheric and coronal UV and X-ray emissions from stars using satellites like Hubble and Chandra. Dr. Wood is the current principal investigator of the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument on board NASA's STEREO mission. He received a PhD in astrophysics from the University of Colorado Boulder.

PANEL ON THE PHYSICS OF MAGNETOSPHERES

LYNN M. KISTLER, *Chair*, is a professor of physics at the University of New Hampshire's Department of Physics and Astronomy and director of the Space Science Center. Dr. Kistler's research interests and activities include the impact of heavy ions on dynamics of the magnetosphere—in particular, the ring current and the magnetotail—and the space instrumentation to measure ion composition. She has been involved in developing instruments for Cluster, Fast Auroral Snapshot Explorer (FAST), Equator-S, Advanced Composition Explorer (ACE), Solar Terrestrial Relations Observatory (STEREO), and Solar Orbiter missions. Dr. Kistler is an AGU Fellow and has been involved in various NASA committees, including the NASA Heliophysics Advisory Committee, the NASA Sun–Earth Connections Roadmap Committee, the NASA Heliophysics Lunar Science Subpanel, and the NASA Heliospheric Mission Planning Working Group. She served as the secretary for the AGU Space Physics and Aeronomy subsection on Magnetospheric Physics. Dr. Kistler earned a PhD in physics from the University of Maryland, College Park. She served as a member of the previous decadal survey's Panel on Solar Wind–Magnetosphere Interactions.

LAUREN W. BLUM is an assistant professor in the Astrophysical and Planetary Sciences Department and the Laboratory for Atmospheric and Space Physics at the University of Colorado Boulder. Prior to joining the University of Colorado Boulder, Dr. Blum was a research astrophysicist at the NASA GSFC and a postdoctoral scholar at the University of California, Berkeley. Her research interests include heliospheric physics and the coupled nature of plasma populations in planetary magnetospheres. Recent work has focused on wave–particle interactions, solar wind–magnetosphere interactions, and energetic particle dynamics in Earth's Van Allen radiation belts. Dr. Blum's experience includes analysis of particle and field measurements from satellites, balloons, and ground stations, as well as instrument and small satellite development. Dr. Blum is the recipient of numerous awards, including AGU's Basu US Early Career Award for Research in Sun–Earth Systems Science. She earned a PhD in aerospace engineering sciences from the University of Colorado Boulder.

IAN J. COHEN is a senior professional staff member and assistant group supervisor of the Geospace and Earth Science Group at JHU/APL. Dr. Cohen primarily focuses on energetic particle dynamics, planetary magnetospheres, magnetosphere-ionosphere coupling, and particle flight instrumentation. He currently serves as deputy lead for the Energetic Particle Detector investigation on the Magnetospheric Multiscale (MMS) mission and deputy project scientist on the Interstellar Mapping and Acceleration Probe (IMAP) mission. Dr. Cohen chairs the AGU Space Physics and Aeronomy section's advocacy committee and is serving on both the NSF Geospace Environment Modeling Steering Committee and the NASA Living With a Star Executive Committee. He earned a PhD in physics from the University of New Hampshire.

ROBERT W. EBERT is a principal scientist at the Southwest Research Institute and an adjoint faculty at the University of Texas at San Antonio. Dr. Ebert's areas of expertise are ion and electron properties and dynamics in Jupiter's magnetosphere and auroral regions; solar wind interactions at Jupiter's magnetopause; solar wind physics—spatial variations and long-term trends; origin, acceleration, and transport of energetic heavy ions in interplanetary space; solar wind instrument development for space weather applications; and graphene foil technology for advanced plasma and energetic neutral atom instruments. He has been involved in mission concept development for heliophysics and planetary science. Dr. Ebert received a PhD in space physics from the University of Texas at San Antonio.

CHRISTINE GABRIELSE is a research scientist at the Aerospace Corporation. Dr. Gabrielse's research interests include studying both the magnetosphere and ionosphere and how they couple, using satellite constellations and ground-based data to study particle energization and precipitation. She is currently on a NASA Geospace Dynamics Constellation (GDC) interdisciplinary scientist team and is the deputy observations section head of the Community for the Unified Study of Interhemispheric Asymmetries (CUSIA) DRIVE Center studying asymmetries in the geospace system. Previous mission teams include NASA's Time History of Events and Macroscale Interactions (THEMIS), Magnetospheric Multiscale Mission (MMS) Energetic Particle Detector Suite (EPD), and Van Allen Probes Magnetic Electron Ion Spectrometer (MagEIS) teams. Dr. Gabrielse is the particle detector instrument PI for Goddard's Geosynchronous Transfer Orbit Satellite (GTOSat) mission. She is the vice chair of NSF's Geospace Environment Modeling community and a focus group leader on the topic of magnetotail dipolarizations (and associated mesoscale phenomena). Dr. Gabrielse received a PhD in geophysics and space physics from the University of California, Los Angeles.

MICHAEL HARTINGER is a research scientist at the Space Science Institute. Dr. Hartinger studies ultra-low-frequency waves and other phenomena related to solar wind–magnetosphere–ionosphere coupling—how energy flows between the Sun and different regions in the near-Earth space environment. His recent research focuses on wave-particle interactions in the Earth's radiation belts and north–south hemisphere asymmetries in the solar wind–magnetosphere–ionosphere system and on co-managing an array of autonomous instruments in Antarctica. Dr. Hartinger received a PhD in geophysics and space physics from the University of California, Los Angeles.

RALUCA ILIE is an associate professor at the University of Illinois, Urbana-Champaign. Dr. Ilie's research interests include kinetic theory and modeling, multiphysics large-scale simulations of plasma transport and dynamics, and developing theoretical and predictive models of the space environment. She is the recipient of numerous awards and honors, including the NSF Geospace Environment Modeling Postdoctoral fellowship, the International Space Science Institute Early Career scientist award, the Air Force Office of Scientific Research Young Investigator Program, the NSF CAREER award, and the NASA Heliophysics Early Career Investigator award. Dr. Ilie received a PhD in space and planetary physics from the University of Michigan.

ENNIO R. SANCHEZ is a senior research physicist at SRI International. Dr. Sanchez's research is focused on the development of techniques to map unambiguously the dynamic magnetotail magnetic field using beams of relativistic electrons, modeling of the M-I mass coupling through ion outflow, and testing the validity of wave–particle mechanisms thought to cause energetic electron precipitation from the radiation belts to the atmosphere. While a postdoctorate researcher at the Johns Hopkins Applied Physics Laboratory, Dr. Sanchez developed models of ion energization in substorms as well as models of electrodynamic M-I coupling. He received a PhD in atmospheric sciences and meteorology from the University of California, Los Angeles.

MICHAEL A. SHAY is a professor in the Department of Physics and Astronomy, University of Delaware. Dr. Shay studies plasma physics using analytical theory and massively parallel computer simulations. His work is applicable to a diverse set of phenomena: solar flares and coronal mass ejections on the Sun, Earth's magnetosphere and space weather, star formation in astrophysical molecular clouds and accretion disks, and controlled fusion devices such as the tokamak. Dr. Shay's research focuses on multiscale phenomena in which short scales (length and time) are intrinsically linked to long scales, making them extremely difficult to simulate using conventional brute force methods. He has extensively studied one multiscale process called magnetic reconnection, in which large amounts of magnetic energy are explosively released in the form of energetic particle acceleration, heating, and plasma flows, and he is also studying novel simulation techniques that may provide a means to directly simulate multiscale phenomena. Dr. Shay received a PhD in plasma physics from the University of Maryland, College Park. He served as a member of the previous decadal survey's Panel on Solar Wind–Magnetosphere Interactions.

PETER D. SPIDALIERE is a retired NASA mission systems engineer and served as the lead engineer on the First Hubble Servicing Mission, Landsat 7, Earth Observing 1, Magnetospheric Multiscale Mission, and Plankton, Aerosol, Cloud, Ocean Ecosystem Mission. Mr. Spidaliere was the systems engineering manager for the International Space Station and the Shuttle upgrades program. Currently, Mr. Spidaliere is an independent consultant for Redwire Space and Southwest Research Institute. He received a BS in mechanical engineering from Virginia Tech.

DIMITRIOS VASSILIADIS is a physical scientist at the National Oceanic and Atmospheric Administration (NOAA). Prior to NOAA, Dr. Vassiliadis was a space physicist at the NASA GSFC, conducting research on magnetospheric and geomagnetic physics. Research interests include solar wind–magnetosphere coupling, high-latitude ionospheric electrodynamics, inner magnetosphere current, and particle dynamics. Dr. Vassiliadis's responsibilities at NOAA include projects in space weather physics and space mission development at the NOAA National Environmental Satellite, Data, and Information Service. He received a PhD in plasma physics from the University of Maryland, College Park.

BRIAN WALSH is an associate professor of mechanical engineering at Boston University. Dr. Walsh's research interests include space and plasma dynamics in planetary space environments, including the plasma interactions in the near-Earth environment and the coupling of energy from the sun into Earth's magnetic system. Dr. Walsh is involved in the NASA missions Time History of Events and Macroscale Interactions (THEMIS) and Magnetospheric Multiscale Mission (MMS) and is part of the development of space-based instrumentation, including small spacecraft and soft X-ray technology that takes images of the interaction of the Sun and solar wind with the Earth's plasma environment to provide a global picture. He received a PhD in astronomy from Boston University.

SHASHA ZOU is an associate professor in the Department of Climate and Space Sciences and Engineering at the University of Michigan. Dr. Zou's research focuses on the dynamic interactions between the Earth's magnetosphere, ionosphere, and thermosphere during geomagnetic disturbances and their space weather impacts. In addition, she is an editor for the AGU journal *Space Weather*. Dr. Zou was awarded the University of Michigan Ted Kennedy Family Faculty Team Excellence Award in 2019 and the URSI (International Union of Radio Science) Young Scientist Award in 2014. She received a PhD in space physics from the University of California, Los Angeles.

PANEL ON THE PHYSICS OF IONOSPHERES, THERMOSPHERES, AND MESOSPHERES

PHILIP J. ERICKSON, *Co-Chair*, is an associate director at Haystack Observatory, a multidisciplinary radio and radar remote sensing observatory that is a subsidiary of MIT. Dr. Erickson also holds the appointment of principal research scientist at MIT. His research interests include basic and applied space weather; atmospheric and ionospheric physics; radar and radio signal processing; nonlinear radiation belt particle acceleration; and radio science, including scattering from plasma irregularities at VHF frequencies and above. Dr. Erickson directs the Atmospheric and Geospace Sciences group at MIT Haystack, co-leads the extensive Haystack education and public outreach effort, and is the lead PI for the NSF-supported Millstone Hill Geospace Facility, which includes a large-aperture, high-power UHF ionospheric radar system. He is the PI for the NASA Auroral Emission Radio Observer (AERO) CubeSat, which will study the radio aurora at HF frequencies from a low-altitude polar Earth orbit using an advanced electromagnetic vector sensor. He is also on the scientific steering committee for the

HamSCI citizen science collective, a national effort using the efforts of more than 700,000 U.S. radio amateur efforts for professional research. Dr. Erickson serves on the Committee on Radio Frequencies. He received a PhD in space plasma physics from Cornell University.

LARA WALDROP, *Co-Chair*, is an associate professor and Y.T. Lo fellow in electrical and computer engineering at the University of Illinois, Urbana-Champaign. Dr. Waldrop's research interests and areas include the study of atmospheric and ionospheric measurements, atmospheric and ionospheric theory, radio and optical wave propagation, remoting sensing, charge particle physics and engineering, computational science and engineering, data science and analytics, photonics of optical engineering and systems, and sensing systems. She is the PI of the NASA Global Lyman-Alpha Imagers of the Dynamic Exosphere (GLIDE) mission, which will measure the far ultraviolet light emitted by hydrogen atoms in Earth's outermost atmospheric layer. Dr. Waldrop is the recipient of numerous awards, including the Y.T. Lo Fellowship in Electrical and Computer Engineering, the NSF CAREER award, and the NSF CEDAR Postdoctoral Award. She received a PhD in astronomy and space physics from Boston University.

REBECCA L. BISHOP is a principal scientist at the Aerospace Corporation in the Space Science Application Laboratory. At the Aerospace Corporation, Dr. Bishop has led the design, building, and testing of a CubeSat-capable GPS radio occultation (RO) sensor to measure ionospheric density and scintillation. Dr. Bishop is the PI of a CubeSat mission to study a nighttime feature in the ionosphere/thermosphere. She has provided a GPS RO sensor on three CubeSat/Nanosat missions and is preparing for a fourth. Dr. Bishop was the Aerospace Corporation PI for the joint Naval Research Laboratory/Aerospace Remote Atmospheric and Ionospheric Detection System (RAIDS) experiment on the International Space Station. In addition, she has been a part of several sounding-rocket experiments. Her research interests include mid- and low-latitude ionospheric dynamics and instabilities, the response of the ionosphere from coupling to the thermosphere, and the reaction of the ionosphere to other regions above and below the ionosphere as well as its influence on those regions. Dr. Bishop explores how the dynamics of the ionosphere impact operational and civil systems such as GPS navigation and communication systems. Another area of interest is to improve communication between the science community and end users to better inform users of the potential impacts of the space environment on their technology. Dr. Bishop is a member of the National Weather Service Space Weather Advisory Group. She received a PhD in physics from the University of Texas at Dallas.

JOHN T. CLARKE is a professor of astronomy at Boston University. Dr. Clarke's main research interests are in planetary atmospheres, their auroral and airglow emission, and ultraviolet space instrumentation. Prior to joining the faculty at Boston University, Dr. Clarke worked at space science laboratories at the University of California, Berkeley, NASA's Marshall and Goddard Space Flight Centers, and the University of Michigan. He served as the deputy project scientist for the Hubble Space Telescope project from 1984–1987, was a science team member on the Wide Field and Planetary Camera 2 project, and has participated in the flight of six sounding rocket experiments. Dr. Clarke is presently the PI for the Venus Spectral Rocket (VeSpR) sounding rocket project, and a Co-I on several space missions, including the Ultraviolet Imaging Spectrograph Subsystem (UVIS) instrument on Mars Atmosphere and Volatile Evolution (MAVEN); the Probing of Hermean Exosphere by Ultraviolet Spectroscopy (PHEBUS) experiment on BepiColombo, ESA's first mission to Mercury; and the ultraviolet imaging spectrograph instrument on the Juno Jupiter orbiter. Dr. Clarke is the deputy PI for the NASA Global Lyman-Alpha Imagers of the Dynamic Exosphere (GLIDE) mission. He received a PhD in physics from JHU.

SEEBANY DATTA-BARUA is an associate professor of mechanical and aerospace engineering at Illinois Institute of Technology (IIT). Dr. Datta-Barua's research interests include the use of Global Navigation Satellite Systems (GNSS) for remotely sensing the atmosphere and Earth's surface, tomography, and data assimilation for ionospheric and thermospheric prediction of dynamics, and in mitigating upper atmospheric effects on GPS-based navigation systems. Current projects include the Lagrangian coherent structures in the ionosphere and thermosphere, auroral E and F region irregularities with a GPS scintillation array, GNSS reflectometry for surface ice monitoring, ionospheric data assimilation and analysis of geomagnetic storms, and the atmospheric effects on GPS-based navigation.

Dr. Datta-Barua is the recipient of numerous awards, including the National Science Foundation CAREER award, the Excellence in Teaching Award at IIT, the Per Enge Earl Achievement Award from the Institute of Navigation, and the Excellence in Research award from IIT. She received a PhD in aeronautics and astronautics from Stanford University.

RICHARD J. FITZGERALD is the project manager for NASA's Dragonfly mission to Titan at the JHU/APL. Mr. Fitzgerald has extensive experience in space flight development and project management. He previously served as program area manager for civil space, as well as project manager for the Van Allen Probes mission and several other APL projects. Prior to APL, Mr. Fitzgerald served as project manager for the Mars Laser Communications Demonstration and mission manager for the Gravity Recovery and Climate Experiment (GRACE), Orbiting Carbon Observatory (OCO), and Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observations (CALIPSO) missions at NASA GSFC. Mr. Fitzgerald is a recipient of the NASA Exceptional Service Medal. He received an MS in computer science from the George Washington University.

KATELYNN R. GREER is a research associate for the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado Boulder. Dr. Greer's research interests include the study of middle atmospheric weather, neutral atmospheric waves in the middle and upper atmosphere, thermospheric composition, coupling events of the entire atmospheric column (such as Sudden Stratospheric Warmings), and remote sensing techniques. Dr. Greer is the deputy PI of the Occultation Wave Limb Sounder (OWLS) instrument on InspireSat III, a project scientist of the Global-Scale Observations of Limb and Disk (GOLD) mission, and an interdisciplinary scientist on the Geospace Dynamics Constellation (GDC) mission. She is a member of the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) Science Steering Committee. Dr. Greer is a recent recipient of the NASA Early Career Public Achievement Award. She received a PhD in aerospace engineering sciences from the University of Colorado.

BRIAN J. HARDING is an assistant research physicist in the Space Sciences Laboratory at the University of California, Berkeley. Dr. Harding's research is focused on the dynamics of the Earth's upper atmosphere and ionosphere. He is responsible for the neutral wind data product for the NASA Ionospheric Connections Explorer (ICON) mission and served as the chair of ICON's electrodynamics working group. Dr. Harding also deploys and operates ground-based airglow imagers and interferometers to study wind–wave interactions in the thermosphere. His research interests include optical instrumentation, inverse theory, photochemical and radiative transfer modeling, and ionospheric electrodynamics. Previously, Dr. Harding was a postdoctoral research associate at the University of Illinois at Urbana-Champaign. He received a PhD in electrical engineering with a focus in remote sensing and space sciences from the University of Illinois at Urbana-Champaign.

AMY KEESEE is an associate professor in the Department of Physics and Astronomy and the Space Science Center at the University of New Hampshire. Dr. Keesee studies ion dynamics in the magnetosphere, focusing on the plasma sheet and magnetotail regions, especially during magnetospheric storms and substorms. She also works on instrument development, including a next-generation plasma spectrometer for space and laboratory measurements, and has developed an education and outreach program on the Sun and space weather. Previous research interests included laboratory plasma physics, with an emphasis on laser-based diagnostics. Dr. Keesee received a PhD in plasma physics from West Virginia University.

KRISTINA A. LYNCH is a professor of physics in the Department of Physics and Astronomy at Dartmouth College. At Dartmouth, Dr. Lynch has led the design, manufacturing, testing, and launch of a number of NASA auroral sounding rocket payloads. Her research interests include instruments that measure ionospheric plasma particles and fields, the plasma physics of the lower thermal ionosphere, laboratory plasma physics used to develop space instrumentation, and developing and analyzing space mission architectures for low-resource ionospheric multipoint missions. Previously, Dr. Lynch was on the research faculty of the University of New Hampshire, in the Department of Physics and the Institute for Earth Oceans and Space. Dr. Lynch is a recipient of an NSF CAREER Award. She received a PhD in physics from the University of New Hampshire.

DANIEL R. MARSH is a senior scientist at the National Center for Atmospheric Research's Climate and Global Dynamics Laboratory and a professor at the University of Leeds. Dr. Marsh's research interests and activities include whole atmosphere modeling, middle atmosphere composition and solar–terrestrial coupling, and the interaction of chemistry and dynamics in the mesosphere and lower thermosphere. Dr. Marsh is the chair in Comparative Planetary Atmospheres and a member of the executive committee at the Priestley International Centre for Climate. He also serves as the vice president of the Scientific Committee on Solar Terrestrial Physics and is the recipient of the NASA Group Achievement awards for the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) and the Upper Atmosphere Research Satellite (UARS) missions. Dr. Marsh received a PhD in atmospheric and space sciences from the University of Michigan.

PHIL G. RICHARDS is a professor emeritus from the University of Alabama in Huntsville and a research professor (retired) in the Department of Astronomy and Astrophysics at George Mason University. Previously, Dr. Richards was a discipline scientist at NASA headquarters. He has over 40 years of experience in space science, specializing in numerical techniques for studying ionospheric transport phenomena, ionospheric chemistry, absorption of solar irradiance, and ionospheric photoelectron theory. Dr. Richards was awarded the University of Alabama in Huntsville Foundation Award for Research Excellence. He received a PhD in space physics from La Trobe University, Bundoora, Victoria, Australia.

PANEL ON SPACE WEATHER SCIENCE AND APPLICATIONS

CHRISTINA M.S. COHEN, *Co-Chair*, is a member of the professional staff at the California Institute of Technology. Dr. Cohen's research currently focuses on the acceleration, transport, and properties of solar energetic particles in the heliosphere and their space weather implications. She is past president of the Space Physics and Aeronomy Section of the AGU. Dr. Cohen led a team that produced the report for NASA *Next Steps in Determining Space Weather Benchmarks for Ionizing Radiation Hazards*. Dr. Cohen was co-chair of the organizing committee for the National Academies' Space Weather Operations and Research Infrastructure Workshop, Phase II. She received a PhD in physics from the University of Maryland, College Park.

THOMAS P. O'BRIEN III, *Co-Chair*, is a research scientist in the Space Sciences Department at the Aerospace Corporation. Dr. O'Brien's research experience includes magnetospheric physics, with special emphasis on radiation belts and empirical analysis of in situ particle data. He is a past chair of the COSPAR Panel on Radiation Belt Environment Modeling (PRBEM) and editor of the journal *Space Weather*. Dr. O'Brien is a member of the NASA Space Weather Council, a community-based, interdisciplinary forum that provides advice to the NASA's Heliophysics Advisory Committee (HPAC), which in turn provides advice to NASA's Heliophysics Division. He received a PhD in geophysics and space physics from the University of California, Los Angeles.

HAZEL M. BAIN is the CIRES science lead at the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center and a research scientist in the University of Colorado Boulder's Cooperative Institute for Research in Environmental Sciences (CIRES). Dr. Bain's current research focuses on space weather and, in particular, solar radiation storms, which can pose a radiation hazard for astronauts in space and for passengers and crew on polar flight routes, as well as causing satellite malfunctions and problems for high-frequency communication technologies. Dr. Bain previously worked at the Space Sciences Laboratory at the University of California, Berkeley, and did research on solar flares as a member of the NASA Reuven Ramaty High Energy Spectroscopic Imager (RHESSI) spacecraft team. She was also part of a team that designed and built a solar gamma-ray telescope, which flew on a high-altitude balloon around Antarctica. Dr. Bain received a PhD in physics and astronomy from the University of Glasgow.

THOMAS E. BERGER is the founder and executive director of the Space Weather Technology, Research, and Education Center at the University of Colorado Boulder. Dr. Berger's research interests include the observation and analysis of solar magnetic structures, from the smallest observable magnetic elements to the plasma instabilities in large-scale prominences, and application of machine learning to space weather prediction and data assimilation problems. Prior to joining the University of Colorado, he was the director of the NOAA/NWS Space Weather Prediction Center, a project scientist at the NSF Daniel K. Inouye Solar Telescope at the National Solar Observatory, and a senior research scientist at Lockheed Martin's Solar and Astrophysics Laboratory. Dr. Berger served as the Working Group Four lead at the White House Office of Science and Technology Policy's Space Weather Operations, Research, and Mitigation task force and was the founding chair of the American Astronomical Society's Solar Physics Division's Public Policy Committee and Nomination Task Force. He has served on numerous NASA and NSF committees and panels, and is a member of AGU's Space Physics and Aeronomy Division Nominations Task Force. Dr. Berger received a PhD in applied physics and astrophysics from Stanford University.

YAIRESKA M. COLLADO-VEGA is a project scientist at NOAA National Environmental Satellite, Data, and Information Service in the Office of Space Weather Observations. Formerly, Dr. Collado-Vega was the director of the Moon to Mars Space Weather Analysis Office at NASA GSFC, which supports NASA's Space Radiation Analysis Group (SRAG) with human space exploration activities by providing novel capabilities to characterize the space radiation environment and also provides real-time analysis of the space environment and probable impacts for NASA missions. Dr. Collado-Vega's research focuses on the solar wind interaction with Earth's magnetic environment, solar energetic particle events, and space weather real-time analysis. She also works on the validation of solar and magnetospheric models and the current developments on machine learning capabilities to improve space weather analysis and forecasting. Dr. Collado-Vega is the former lead of the experimental Space Weather Forecasting Team at the Community Coordinated Modeling Center and conducts education and public outreach for NASA and the Heliophysics Science Division. She received a PhD in space physics from the Catholic University of America.

HEATHER ELLIOTT is a staff scientist and acting lead for the heliospheric group at the Southwest Research Institute. Dr. Elliott's research interests include the analysis of large-scale structure in the solar wind, space weather impact on geophysical indices, and the global positioning system. Dr. Elliott is also an adjoint professor at the University of Texas, San Antonio, and serves as a member of the Living With a Star program Analysis Group at NASA. She received a PhD in space plasma physics from the University of Alabama, Huntsville.

NOÉ LUGAZ is a research professor in the Space Science Center and Department of Physics, Institute for the Study of Earth, Oceans, and Space at the University of New Hampshire. Dr. Lugaz's research focuses on the investigation of coronal mass ejections (CMEs), particularly series of CMEs, their propagation, and their consequences on Earth's magnetosphere and radiation belts, and for the acceleration of particles. His work encompasses solar, interplanetary, and magnetospheric/radiation belt physics, through the analysis of remote-sensing observations and in situ measurements and numerical simulations. Dr. Lugaz is the lead of the Interstellar Mapping and Acceleration Probe (IMAP) student collaboration, a 3U CubeSat mission to Earth's cusps. He currently serves as the editor-in-chief of *Space Weather* and the chair of the NSF's Solar Heliospheric and Interplanetary Environment (SHINE) steering committee. Dr. Lugaz received a PhD in space physics from the University of Michigan.

JUHA-PEKKA LUNTAMA is head of Space Weather Office at the ESA. ESA is a key U.S. partner in the development of space weather observational assets. Mr. Luntama's research focuses on high-resolution ionospheric imaging by tomography. He provides addition insight into the international context for the space weather enterprise.

STEVEN K. MORLEY is a scientist in the Space Science and Applications division of the Los Alamos National Laboratory (LANL). Dr. Morley was also a postdoctoral researcher at LANL, a postdoctoral fellow at the University of Newcastle, a research associate at the Rutherford Appleton Laboratory, and a postdoctoral researcher at the

British Antarctic Survey. His research interests include electron radiation belt climatology and dynamics, geomagnetic substorm occurrence and space weather impacts, inner magnetosphere dynamics and wave-particle interaction, and geomagnetically induced currents. Dr. Morley received a PhD in physics from the University of Southampton.

EMMA L. SPANSWICK is an assistant professor in the Department of Physics and Astronomy and Tier 2 Canada Research Chair in Geospace Dynamics and Space Plasma Physics at the University of Calgary. Dr. Spanswick develops ground- and satellite-based instruments to improve understanding of Earth's near-space environment and space weather. Her research interests include energization, transport, and loss of the >30 keV electron population in the near-Earth space environment; magnetosphere-ionosphere coupling mechanisms; techniques for remote sensing magnetospheric dynamics; and impacts of particle precipitation on the ionosphere and technological systems. Dr. Spanswick earned a PhD in physics from the University of Calgary.

DREW L. TURNER is a senior research staff at JHU/APL. Dr. Turner's research interests include energetic charged particles in the Earth's magnetosphere; the coupling of energy from the Sun and space environments ranging from the Van Allen radiation belts to the boundaries of the magnetosphere and solar wind; and space-based measurements needed to improve space weather forecasting, nowcasting, and hindcasting. Dr. Turner is a 2018 James B. Macelwane Medal Winner from the AGU. He received a PhD in aerospace engineering from the University of Colorado Boulder.

KATHRYN WHITMAN is a research scientist in the Space Radiation Analysis Group (SRAG) at NASA Johnson Space Center. SRAG is responsible for ensuring that the radiation exposure received by astronauts remains below established safety limits. Dr. Whitman's work includes space weather, solar energetic particles, and galactic cosmic rays and their impacts on the space radiation environment. A primary focus is the development of a validation process to assess SEP forecast models selected for use in space radiation operations during NASA's Exploration Class missions. Dr. Whitman received a PhD in physics from the University of Hawai'i at Manoa.

MICHAEL WILTBERGER is the deputy director of the High Altitude Observatory (HAO) at the National Center for Atmospheric Research. Dr. Wiltberger was the section head of the Geospace Section in the Atmospheric and Geospace Science Division at NSF. His research interests include the modeling of the magnetosphere and its interaction with the solar wind and coupled thermosphere–ionosphere system. Dr. Wiltberger's work also entails the inclusion of ionospheric outflow and the application of advanced statistical analysis in global models and groundbreaking results proving the connection between localized reconnection and so-called Bursty Bulk Flows in high-resolution simulations of the magnetotail. Dr. Wiltberger also served in many community functions, including as chair of the Geospace Environment Modeling (GEM) Steering Committee, and as vice chair of the American Meteorological Society Science and Technology Committee on Space Weather. He received a PhD in space plasma physics from the University of Maryland, College Park.

PANEL ON THE STATE OF THE PROFESSION

APRILLE J. ERICSSON, *Co-Chair,* became Assistant Secretary of Defense for Science and Technology on March 29, 2024. Prior to this appointment, she served as the business lead in the Instrument Systems and Technology Division at the NASA GSFC. Dr. Ericsson has also served at GSFC as acting chief technologist, project manager, deputy to the chief technologist for the Engineering and Technology Directorate, program executive for Earth science, and business executive for space science. For 10 of those years, she was an instrument project manager leading spaceflight mission teams. Dr. Ericsson has a breadth of experience in astrophysics, heliophysics, and planetary and Earth science that includes the James Webb telescope; Ice, Cloud, and Land Elevation Satellite (ICESat-1 & 2); lunar orbiters; and the Sample Collection for Investigation of Mars (SCIM) missions. She has held adjunct faculty appointments at several universities, and served on boards at the National Academies, MIT, and as a former Howard University Trustee. Dr. Ericsson is co-founder and advisor of the nonprofit STEM Youth Dynamic

Mathematical Visionaries National Society of Black Engineers, Jr. Chapter in the Washington, DC. In these roles, Dr. Ericsson has been an outspoken and tireless champion for the advancement of people of color and women in the STEM fields. As such, she has spoken extensively throughout the world, presenting papers on her technical research and speaking on diversity, equity, and inclusion in the United States, Canada, Germany, Netherlands, England, South Africa, Mexico, Portugal, and Brazil. Dr. Ericsson is the first African American woman to receive a PhD in mechanical engineering, the aerospace option, from Howard University, and the first African American female to receive a PhD in engineering as a civil servant at NASA GSFC.

MARK B. MOLDWIN, *Co-Chair,* is the Arthur F. Thurnau Professor of Climate and Space Sciences and Engineering and Applied Physics at the University of Michigan's (UM's) Department of Climate and Space Sciences and Engineering within the College of Engineering. Dr. Moldwin is also affiliated with the Space Physics Research Laboratory, the Engineering Education Research program, the African Studies Center, the Michigan Institute for Plasma Science and Engineering, and the Robotics Institute. He is the faculty director of UM's M-STEM M-Engineering program, past president of AGU's Education Section, and executive director of NASA's Michigan Space Grant Consortium. Prior to joining the faculty of UM, Dr. Moldwin was a professor of space physics at UCLA, a professor of physics and space sciences at Florida Institute of Technology in Melbourne, and a postdoctoral research fellow in the Space and Atmospheric Sciences and Nonproliferation and International Security groups at Los Alamos National Laboratory. He received a PhD in astronomy and space physics from Boston University.

JIMEZ ASHBY, JR., is a human capital and organizational transformational practitioner with a focus in industrial–organizational psychology and diversity, equity, inclusion, and accessibility (DEIA) plus justice. Mr. Ashby has several years of highly progressive experience, spanning a wide range, to include human resources and DEIA strategic implementation to human-centered design and workforce planning and analytics. He has worked with clients within higher education, finance, construction, retail, consumer goods, technology, advertising, and health care as well as the federal sector. Mr. Ashby also has a global footprint, having supported workforces and organizations in Canada, Mexico, and the United Kingdom as well as foreign service and deployed personnel. His community service roles include co-chair for the Council on Access, Equity, and Justice; Human Rights Commissioner—Commonwealth of Virginia; member of the Virginia Commonwealth University Employer Advisory Board; and member of the Society for Human Resource Management. Mr. Ashby received a BA in experiential learning, organizational structure, and cultural diversity from George Mason University.

DOROTHY CARTER is an associate professor of psychology at Michigan State University and director of the Leadership, Innovation, Networks, and Collaboration Laboratory. Dr. Carter's research interests include efforts to understand how personality and other compositional factors impact team performance, understand the drivers and outcomes of leadership networks within and across teams, develop and validate interventions to support multiteam system performance throughout long-duration space exploration missions to Mars, enable effective leadership and teamwork within scientific research centers, and identify and support the patterns of leadership and communication networks among senior leaders that enable strategic alignment and organizational performance. Dr. Carter received a PhD in industrial/organizational psychology from the Georgia Institute of Technology.

LINDSAY VICTORIA GOODWIN is an assistant professor of physics at the Center for Solar–Terrestrial Research at the New Jersey Institute of Technology (NJIT). Prior to this position, Dr. Goodwin was a Jack Eddy postdoctoral fellow; a postdoctoral researcher at NJIT; a postdoctoral associate at Boston University; a graduate student research assistant, tutor, teaching assistant, and instructor at the University of Saskatchewan; and a summer research assistant at the Rothney Astrophysical Observatory. She received a PhD in physics from the University of Saskatchewan.

McARTHUR JONES, JR., is a research physicist with the Space Science Division of the Naval Research Laboratory. Prior to joining the Naval Research Laboratory, Dr. Jones was a graduate research assistant at the National Center for Atmospheric Research. His research interests include studying the mesosphere and lower thermosphere dynamics, modeling of the mesosphere–thermosphere–ionosphere–magnetosphere system, atmospheric tides, coupling between the upper and lower atmosphere via wave transport, and upper atmospheric climate. Dr. Jones is the recipient of numerous awards and honors, including the Ford Foundation predoctoral fellowship. He received a PhD in aerospace engineering sciences from the University of Colorado Boulder.

SHERI KLUG BOONSTRA is the PI of NASA's Lucy Student Pipeline and Competency Enabler Program, which is NASA's Lucy Asteroid Mission Student Collaboration at Arizona State University (ASU). Ms. Klug Boonstra is also the director of strategic partnerships and co-instructor for the ASU Space Works Program. She has more than 20 years of experience in creating and implementing national NASA STEM education pipeline programs that stretch vertically from precollege to workforce, including as PI for NASA's largest undergraduate internship program. In addition to these duties, Ms. Klug Boonstra is director of the Mars Education Program, which produced and implemented NASA's award-winning Mars Student Imaging Project. Ms. Klug Boonstra has worked on multiple NASA projects, including Mars Odyssey, Mars Exploration Rovers, Lucy Asteroid Mission, Mars Sample Return, Lunar Reconnaissance Orbiter, and astrobiology projects. Prior to ASU, she was the national director of NASA Undergraduate Student Research Program Internships at the University Space Research Association. Ms. Klug Boonstra received the Excellence in Earth and Space Science Education award from the AGU. She received an MS in Earth science education from Boise State University.

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