Early Career Investigator Program
Abstracts of Selected Proposals
(NNH20ZDA001N-ECIP)

Below are the abstracts of proposals selected for funding for the Early Career Investigator program. Principal Investigator (PI) name, institution, and proposal title are also included. 54 proposals were received in response to this opportunity. On December 3, 2020, 15 proposals were selected for funding.

Nada Al-Haddad/University of New Hampshire, Durham
Investigating the Structure of Coronal Magnetic Eruptions Through Comprehensive Data Analysis

- Objectives and Science Questions:
We propose an investigation on the magnetic structure of coronal magnetic eruptions (CMEs) based on a comprehensive data analysis study incorporating in situ measurements of magnetic fields and plasma and remote observations. In parallel, we will also develop and validate models and techniques for in situ measurements that better represent the complexity of CME structures as measured remotely and in-situ. Even with several 100s of CMEs measured in situ by ACE, Wind and STEREO, and 1000s measured remotely by LASCO and SECCHI, measurements of CMEs are strongly under-utilized which limits how we can advance our understanding of their structures. For example, reconstruction and fitting techniques often do not take into consideration plasma measurements (except in some cases the radial expansion) even though non-radial flows are common inside CMEs. Most fitting techniques do not use data at second or minute resolution but average the data into bins of 20 minutes to 1 hour. As such, we have significantly more information about the internal structure of CMEs than what we often use. This extends to combining remote and in-situ observations.

In the five years of the study, we will answer the following science questions:
1- What do plasma and remote measurements reveal about the internal structure of CMEs?
2- What improvements of current fitting and reconstruction techniques can be me made in order to reflect a more realistic structure of CMEs?
3- What is the actual magnetic structure of CMEs?

-Methodology:
The methodology relies on data analysis from current and past heliospheric observatories, primarily PSP, Solar Orbiter, STEREO, ACE and Wind. We will take a deep dive into remote and in-situ measurements of CMEs and combine these various measurements and compare different models to develop a clearer picture of CME structure. In parallel, we will also develop and validate models and techniques for in situ measurements to better represent the complexity of CME structures as found in the previous step. In order to get

the heliospheric context of the observations, we will rely on remote observations and simulations to be performed at NASA/CCMC.

-Expected Impact and Relevance to NASA:
This project has the potential to yield truly transformative results: a total change in our paradigm of what a CME is. This work makes use of NASA HSO, including PSP and SolO missions, and addresses research focus areas H1 and H2 of the NASA Heliophysics 2014-2023 Roadmap.

Chihoko Cullens/University of California, Berkeley
Competing Effects of Atmospheric Waves and Solar Inputs on Chemical Species

The coupling between solar forcing variability and the upper atmosphere has important impacts on the Earth s climate system. One of the most effective coupling mechanisms is energetic particle precipitation (EPP) by which the sun can disturb the atmosphere photochemically and thermodynamically. The ionization from EPP can produce an enhanced NOx abundance in the mesosphere and thermosphere, called EPP-NOx, that is subsequently transported down to the stratosphere to further react with the stratospheric ozone. This process is called an indirect effect of EPP (EPP-IE). Recent studies have shown that EPP-IE can further impact the troposphere by a chemical-dynamical coupling in the polar region. Strength of EPP-IE is controlled by both the magnitude of geomagnetic activities (production of EPP-NOx) and the strength of downward transport of EPP-NOx. Gravity waves (GWs) are a major dynamical force driving the downward transport of EPP-NOx. Because small-scale GWs are hard to simulate and observe from space, the relative importance of atmospheric waves with respect to solar variability impacts on chemical species remain unclear and requires a thorough and quantitative analysis.
Recently-improved satellite GW observations begin to provide global GW characteristics from the stratosphere to the lower thermosphere. Combinations of multiple GW global satellite observations cover a wide range of geophysical locations, altitudes, and a large proportion of GW spectrum. Utilizing the rich satellite observations of GWs and chemical species, this work aims to better understand (1) roles of GWs on EPP-IE, (2) relative importance of GWs on EPP-IE compared to the magnitude of geomagnetic activities and planetary waves (PWs), and (3) seasonal and hemispheric variations of GW influences on EPP-IE. The findings from these investigations provide the needed observational constraint on the Sun-climate coupling and will yield a quantitative description about the solar EPP impacts on the Earth atmosphere.
For the proposed work, majority of data will be obtained from the TIMED-SABER and AIM-SOFIE instruments from Heliophysics projects. In addition to that, Aqua-AIRS (Atmospheric Infrared Sounder) observations from NASA's Earth Observing System and ACE (Atmospheric Chemistry Experiment) satellite data will be also used. To supplement observational study, TIME-GCM (Thermosphere-Ionosphere-Meosphere-Electrodinacis General Circulation Model) will be used to conduct sensitivity study of EPP-IE mechanisms. To achieve the project objective, we will first develop databases of GWs, PWs, and chemical species. Joint analyses of three satellite observations will be conducted to cover wide ranges of GW spectrum and latitudes. Secondly, we will

evaluate the correlations between GWs and chemical species variations under various solar and terrestrial disturbing conditions such as geomagnetic activities, the 11-year solar cycle, and PW activities. Finally, mechanisms of EPP-IE and importance of GWs on EPP-IE compared to large-scale PWs and solar conditions will be examined using both satellite data and also sensitivity study using TIEM-GCM.
The proposed work uses currently operating missions of the Heliophysics System Observatory (HSO), TIMED/SABER and AIM/SOFIE. This proposed work directly fits one of the goals of NASA Heliophysics Decadal Survey, Determine the dynamics and coupling of Earth s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.

Simone Di Matteo/University of New Hampshire, Durham
Geo-effectiveness of Solar Wind Periodic Density Structures

Our goal is the study of the geo-effectiveness of solar wind periodic density structures (PDS) in driving magnetospheric Ultra Low Frequency (ULF) waves, investigating both the macroscale and microscale nature of the PDS interaction with Earth s magnetosphere via multi-spacecraft analyses. PDSs constitute a large portion of the slow solar wind. They correspond to advected structures with length-scales equal to or greater than that of the Earth s magnetosphere, namely ranging from a few Earth radii (RE) up to 1000 RE. PDSs are dynamic pressure enhancements that can modulate the size of the magnetosphere cavity and drive compressional oscillations of the magnetospheric field at frequencies determined by the solar wind velocity divided by the PDS length scale. The observed period ranges from several minutes to a few hours, periods that are important for a wide variety of magnetospheric phenomena, including radiation belt particle acceleration, loss and diffusion. However, little is known about the effects of smaller (microscale) PDSs that are often embedded within their larger (macroscale) counterpart. Here, we suggest a possible mechanism. In the interplanetary medium, trains of PDSs often appear as a series of small flux ropes and/or pressure balance structures separated by plasma discontinuities. These interplanetary plasma discontinuities can generate transient kinetic phenomena at the Earth s bow shock like Hot Flow Anomalies and Foreshock bubbles, which in turn can trigger ULF waves. Therefore, the main objectives of this project are to understand (1) what are the properties of ULF waves generated by the impact of PDSs on the magnetosphere and (2) what are the physical correlations between PDSs boundaries and different transient kinetic phenomena at the bow shock.
Data. Solar wind conditions, multi-spacecraft magnetosphere observations, and ground observatories are needed to trace the evolution of PDSs and their effect on the Earth s magnetosphere. The data needed are from Wind / SWE & MFI; GOES / MAG (from 8 to 15); THEMIS / FGM, EFI, & ESA; MMS / FGM, EDI, & FPI; CLUSTER/ FGM, EDI, & CIS; Ground magnetic observatories (INTERMAGNET); Geomagnetic Indices (WDC, Kyoto).
Methods. Recently, we developed a robust spectral analysis method to specifically identify periodic fluctuations in interplanetary (for PDSs) and magnetospheric field (for ULF waves) measurements. Our approach, based on the multitaper method, provide an additional step for the robust identification of the background power spectral density. This allows the identification of statistically significant power enhancements, that when

in agreement with the results of the multitaper harmonic analysis, reveal the occurrence of periodic fluctuations in the data.
Milestones: 1. Create a catalogue of time intervals with periodic fluctuations at similar frequencies in the solar wind density at Wind and magnetospheric field at GOES. 2. Investigate the response of ULF waves to PDSs using also ground magnetic observatories. Focus on possible dependences on solar cycle, seasons, state of the solar wind, geomagnetic indices. 3. Identification of case studies where MMS, THEMIS, and/or CLUSTER are located at the bow shock and/or in the dayside magnetosphere. Reveal the evolution and effect of the small scale PDSs during their interaction with the Earth s magnetosphere. The catalogue of the events and the updated versions of the spectral analysis software will be available online for the community.
While most recent work on PDSs is focused on their solar source, comparatively little is known regarding their role in the solar wind-magnetosphere interaction. The proposed study will give new insights into this chain of interactions triggering ULF waves in the Earth s magnetosphere. As such, this proposal fits within the specific objective to advance our understanding of the Sun s activity, and the connections between solar variability and Earth and planetary space environments.

Alexander Fletcher/Naval Research Lab
Dust Impacts on Spacecraft and Turbulence in Dusty Solar Plasma

Dust grains and meteoroids are pervasive in our solar system and interact with both the background plasma and spacecraft. This project will use theory, simulation, and in-situ data to answer the following science questions:

1) How does dust affect waves in plasmas produced by hypervelocity impacts?

Meteoroids striking spacecraft surfaces at hypervelocity speeds (>~8 km/s) will ionize material, forming a plasma that expands into the surrounding vacuum. Under certain conditions, impact plasmas generate electrostatic fluctuations and electromagnetic pulses (EMPs) that are seen by nearby antennas. This effect has been seen in space (e.g. Cassini, STEREO, WIND, Parker Solar Probe) and ground-based experiments. Impacts also create dust along with plasma, and this dust affects the expansion in the plasma/dust plume and the observed electrostatic fluctuations and EMPs. We developed a simulation pipeline consisting of an MHD-hydrocode (ALEGRA from Sandia National Laboratory) for the impact and a particle-in-cell (PIC) code for the collisionless plasma. We will incorporate dust into these simulations and study a variety of impact regimes to understand how dust alters the behavior of impact plasmas. These simulations will be compared to new data from light gas gun experiments that include dust detectors.

2) How can dust impacts on the Parker Solar Probe (PSP) trigger signals in instruments measuring electromagnetic fields?

The PSP is bombarded by dust and meteoroids as it travels around the Sun. PSP does not have a dust detector, but there is clear evidence of impacts in data from FIELDS and WISPR instruments. While patterns exist in the measurements over many impacts, there are exceptions and features that are not well-understood. We will apply the simulation techniques described above to impact conditions on PSP in order to understand the physical mechanisms that produce the different types of signals in WISPR and FIELDS. The hydrocode component is capable of realistically modeling the geometries and most materials found on PSP. The PIC component will yield expected electromagnetic field measurements. These simulations will be validated against PSP observations of impacts in FIELDS and WISPR.

3) Do rotation waves in multicomponent plasmas contribute to heating and structure in the solar corona?

Multicomponent (i.e. with dust or heavy, high-charge state ions) plasmas are capable of supporting a novel wave mode with a characteristic frequency that represents a first order rotation of the light ion component. Near the rotation frequency, energy can flow efficiently from the waves into the plasma and increase its temperature. A signature of these modes is nonlinear structures that we predict could be seen by FIELDS and SWEAP on PSP. We will use the code mentioned previously to study the nonlinear behavior and quantify the flow of energy from rotation waves to the plasma. Finally, we will analyze data from FIELDS and SWEAP to look for evidence of nonlinear structures in the plasma near the Sun.

The answers to these science questions will provide better understanding of waves in impact-produced plasmas, dust impacts on PSP, and the interaction of dust and turbulence in the corona. This work will contribute to the Heliophysics Research Program objectives (as detailed in the Program Overview) to explore and characterize the physical processes in the space environment (questions 1-3), advance our understanding of the Sun s activity (question 3), and safeguard human and robotic explorers (questions 1/2).

Dale Gary/New Jersey Institute Of Technology
Probing weak energy release in quiescent solar active regions

Background and Motivation:
How the corona is heated to multi-million K and accelerated to produce the solar wind is an outstanding question in heliophysics. One promising mechanism is based on the idea that the corona is heated by a myriad of small-scale energetic impulsive events. If weak energy release events behave as energetically smaller versions of larger flares, the released magnetic energy should be converted into the form of energetic electrons, bulk flows, and heated plasma, and possibly produce observable signatures. However, detailed studies of weak energy release in quiescent active regions (ARs) remain elusive owing to the limited sensitivity of most of the existing facilities and the lack of coordinated investigations at multiple wavelengths. This project is motivated by recent coordinated observations with Jansky Very Large Array (VLA) and a suite of NASA spacecraft (SDO, Hinode, IRIS) that provide observations at multiple wavelengths. In our existing VLA datasets, which are some of the most sensitive to weak radio emission ever obtained, we have identified numerous episodes of coherent radio bursts from energetic electrons in or above quiescent ARs throughout the hours-long observing windows. Each

episode comprises myriad short-lived (tens of milliseconds) bursts that are possibly reminiscent of small-scale electron acceleration events. Another previously reported but largely unexplained phenomenon observed in the radio-burst-hosting ARs is continuous plasma outflows, which are thought to be related to the origin of the slow solar wind. With multi-wavelength observations from ground- and space-based instruments, it is possible to study the candidate signature (coherent radio bursts) of weak energy release events and their relations with the plasma dynamics in the surrounding atmosphere.
Science Objectives:
The overarching goal of the project is to achieve a better understanding of weak energy release processes in the quiescent solar corona. We will guide our investigations using the following specific science questions:
1. Where are the sites for weak magnetic energy release events during quiescent periods? How does the energy release vary spatially and temporally?
2. Are weak coronal energy release events spatially and temporally associated with the observed continuous plasma outflows from active regions?
3. Are weak coronal energy release events associated with any signatures in the lower solar atmosphere?
Methodology:
To achieve the science objectives above, we propose the following investigations:
1) Utilize coherent radio bursts to trace energetic electrons from weak energy release events, which will allow us to:
a) study local plasma properties and dynamics of the radio-emitting sources in space and time, and the implications on the weak energy release events.
b) map magnetic field lines along which the nonthermal electron beams propagate and compare with macroscopic magnetic structures inferred by extrapolation models from photospheric magnetic field maps from SDO/HMI.
2) Examine the spatial and temporal relations between the signatures of energetic electrons and the continuous plasma outflows from ARs seen by SDO/AIA and Hinode/EIS.
3) Explore the spatial and temporal relations between the signatures of energetic electrons in the coronal and their responses in the lower solar atmosphere observed by IRIS and SDO/AIA.
4) Estimate the energy required for individual events accounting for the heating and the kinetic energy in the bulk plasma flows.
Relevance:
Our proposal is highly relevant to the ROSES-2020 B.14 solicitation, as it helps to address the overarching scientific goal Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe designated in the Heliophysics Decadal Survey.

Dustin Hickey/Naval Research Lab
Understanding sources and electrodynamic effects of Medium Scale Traveling Ionospheric Disturbances (MSTIDs) through modeling and observations

The formation and development of Medium Scale Traveling Ionospheric Disturbances (MSTIDs) has long been a compelling science question because of their immediate practical implications for communications and geolocation as well as the fact that they are an illuminating example of the dynamics and coupling between the thermosphere and the ionosphere. MSTIDs are wave-like propagating ionospheric density disturbances with horizontal scales sizes of 100-200 km. The most commonly observed type of MSTID (or AGW-TID) is believed to be caused by Atmospheric Gravity Waves (AGWs), which propagate from the troposphere up through the thermosphere. A second type of MSTID is sometimes referred to as an electrodynamic MSTID (or Electrified-TID), as these structures are accompanied by large electric fields. While significant progress has been made in understanding MSTIDs, many questions remain regarding their formation and the differentiation between AGW-TIDs and Electrified-TIDs.

To better understand these processes, we propose to address three science questions:
1. To what extent is the linear AGW propagation theory capable of predicting the development of AGW-TIDs in the ionosphere?
2. What are the physical processes responsible for the formation of Electrified-TIDs?
3. How do AGW-TIDs and Electrified-TIDs affect ionospheric electrodynamics?

Resolving these MSTID questions will help give us better understanding of the near-Earth space environment. This proposed study addresses the Heliophysics Decadal Survey goal to Determine the dynamics and coupling of Earth s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.

The approach is to combine physics-based modeling to simulate MSTIDs with multi-instrument data analysis. The primary tool for the modeling is SAMI3 (Sami3 is Another Model of the Ionosphere), which is a three-dimensional, first-principles model of the ionosphere. To generate thermospheric AGW fields the DoN s mesoscale weather prediction system, COAMPS® (Coupled Ocean-Atmosphere Mesoscale Prediction System) is used as input for a linear gravity-wave ray model, which propagates the waves up to 400-500 km altitude. The SAMI3 ionosphere will be run with the output from the coupled COAMPS-ray system (which only simulates primary AGWs) in order to determine the limitations of linear AGW theory (Question 1). To establish the physical mechanism responsible for Electrified-TIDs (Question 2), the SAMI3 ionosphere model will be used as in a recent paper by Duly et al. [2014]. As the Duly study was unable to explain all of the Electrified-TID features, it will be used as a starting point. To resolve the question of how AGW-TIDs and Electrified-TIDs affect the ionospheric electrodynamics (Question 3), the electric field output from SAMI3 will be examined and compared.

The modeling provides a vehicle for testing the physics responsible for the generation and propagation of MSTIDs, but in order to determine where the model is acting realistically, it is necessary to compare the output with data. There are many data sources available to study MSTIDs and the surrounding ionosphere, but frequently comparisons utilize only a single source of measurements, as it is time consuming to find time periods with data overlap. Currently available data projects include all-sky imagers (ASIs), ionosondes, Global Navigation Satellite Systems (GNSS) receivers, and the Ionospheric Connection Explorer (ICON). A key focus of this work will be to identify the presence of

MSTIDs in existing measurements and to correlate the time/date for more comprehensive validation of modeling studies. This multi-instrument approach is vital to fully capture the properties of MSTIDs and to resolve the proposed science questions.

Duly, T. M., Huba, J. D., and Makela, J. J. (2014), Self consistent generation of MSTIDs within the SAMI3 numerical model, JGR Space Physics, 119, 6745 6757, doi:10.1002/2014JA020146.

Graham Kerr/Catholic University Of America
Corona to Photosphere: Exploring Solar Flare Energy Transport Throughout the Solar Atmosphere

Solar eruptive events (SEEs) are the fundamental drivers of geoeffective space weather. Magnetic reconnection drives SEEs, liberating a tremendous amount of energy, partitioned into various physical manifestations: particle acceleration, mass and magnetic field eruption, atmospheric heating and the subsequent emission of radiation as solar flares. This proposal will focus on energy transport through the Sun's atmosphere during solar flares. A model of energy transport must be able to describe the full atmospheric response, from the photosphere to corona, not just a localised layer or temperature range. Observational evidence has demonstrated that the standard model of energy transport via beams of nonthermal deka-keV electrons is insufficient to explain lower atmospheric heating and the cooling (particularly of coronal flare loops).

By interrogating predictions from state-of-the-art flare radiation hydrodynamic (RHD) RADYN models (used in combination with post-processing radiation transport codes) with multi-wavelength, multi-spacecraft observations (IRIS, Hinode/SOT, SDO/AIA and GOES), we will demonstrate both the requirement for, and characteristics of, missing ingredients to models. This will improve the overall understanding of energy partitioning during SEEs.

We will explore the roles of: proton beams, Aflvenic waves, return currents, and suppression of thermal conduction. We will forward model observables spanning the interconnected layers of the solar atmosphere. Observables from the corona will include effects of loop geometry and superposition, via RADYN Arcade modeling. Spectroscopic inversions have been used to derive the stratification of the solar atmosphere, with recent applications to flares. We will perform comparisons of inverted atmospheres to RADYN models, initially of Mg II using the IRIS2 tool, with a more detailed follow up study, including additional spectral lines, using the STiC code.

Our main science question (MSQ) will be answered by addressing two sub-questions (SQ):

MSQ - How is energy transported from looptops to the deep solar atmosphere and back during solar flares?

SQ1 - What are the mechanisms operating during flares that heat the deep layers of the solar atmosphere? We will study the results of spectroscopic inversions, the optical continuum, and chromospheric line widths to determine if additional heating by proton beams or downward propagating Alfv\\'enic waves leads to closer consistency with observations.

SQ2 - Are heating by return currents and the suppression of thermal conduction responsible for slow cooling during the flare gradual phase? The modelled gradual phase in loop and arcade models is too short, with efficient thermal conduction leading to rapid cooling. We will explore if suppressing thermal conduction and inclusion of heating via return currents can account for this discrepancy, and to what extent post-impulsive phase heating is required or not.

This will leverage the PI s expertise and leadership in the field of solar flare modeling. The PI is a co-leader of an International Space Sciences Institute team 'Interrogating Field-Aligned Models', through which he is helping to guide the benchmarking, improvement, and coordination of flare modeling. The ECIP would allow the PI to explore these research directions that originated from a successful NASA Postdoctoral Program fellowship.

This project directly addresses a Heliophysics Decadal survey goal to 'discover and characterise fundamental processes that occur both within the heliosphere and throughout the Universe', PSG 1 & 3 of the IRIS Senior Review, and PSG 1 of the Hinode Senior Review.

Lydia Korre/University Of Colorado, Boulder
Dynamical interaction of overshooting convection with magnetic fields in the solar interior

Overview:
Understanding the Sun s almost periodic 22-year-cycle of magnetic activity remains a fundamental challenge in heliophysics. A major step toward addressing this challenge is to gain a better understanding of the role the tachocline plays in the operation of the solar dynamo. The tachocline, which coincides with the interface between the convection zone and the radiative zone, forms the seat of the dynamo in many dynamo models, and yet this dynamically active region remains poorly understood. Discerning the dynamics associated with this interface is therefore of paramount importance for ultimately understanding how the solar dynamo operates. Furthermore, via results stemming from mean-field dynamo models and numerical simulations along with helioseismic observations, it has long been recognized that convective motions, and larger-scale flows (associated with differential rotation and meridional circulation) are all crucial in the operation of the solar dynamo. For these purposes, we have extensively studied overshooting convection in spherical shells via 3D numerical simulations that span a wide parameter space and have also been working on understanding the effect of rotation on these overshooting dynamical processes.

We propose to examine the dynamics that arise from the interaction of these motions with magnetic fields though the use of 3D MHD simulations.
Science Goals and Objectives:
Despite many previous scientific efforts, there is still no fully non-linear model of the solar interior that can capture the dynamics of solar magnetism in a self-consistent way.
Thus, our first goal is to:

1. Understand the dynamical balances taking place within the convection zone and the overshoot region and explore how these could lead to a differentially rotating convection zone, with a uniformly rotating radiative zone and a thin tachocline, self-consistently.

Then, our second task will be to:

2. Use the knowledge from task 1 to study the different dynamical regimes stemming from the interaction of convective motions and large-scale flows with magnetic fields and identify which regimes are the most relevant to the Sun.

Our ultimate goal is to:

3. Combine the knowledge we gain from tasks 1 and 2 to create a self-consistent, fully-nonlinear model which can capture a solar-like cyclic magnetic activity that can be directly compared to observations.

Methodology:
We will run a suite of 3D numerical simulations solving the Navier-Stokes equations in a spherical shell that consists of a convection zone with an underlying stably stratified region by accounting for both rotation and magnetic fields. Our simulations will span a wide range of parameters which will help us examine different dynamo cases and their associated dynamical processes and ultimately identify how to achieve a dynamical regime that is consistent with solar-like stars. These spherical simulations will be performed using the open-source Rayleigh code which solves the MHD Navier-Stokes equations under the anelastic approximation in a rotating spherical shell (for a detailed Data Management Plan see main proposal).
Relevance to NASA s Heliophysics objectives:
This research falls under the broad goal of Advance our understanding of the Sun s activity, and the connections between solar variability and Earth and planetary space environments, the outer reaches of our solar system, and the interstellar medium identified in NASA s Heliophysics overarching goal and guided by the NASA 2014 Science Plan and by the 2013 National Research Council Decadal Strategy for Solar and Space Physics report, Solar and Space Physics: A Science for a Technological Society, and it specifically touches on goals 1 and 4: Determine the origins of the Sun s activity and predict the variations in the space environment , and Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe from the Decadal survey.

Leslie Lamarche/SRI International
Lobe- reconnection-driven Mesoscale Coupling and Energy Deposition in the Ionosphere

Ionospheric plasma convection in the polar cap is driven by magnetic reconnection between the Earth s magnetosphere and the interplanetary magnetic field (IMF). When

IMF Bz is northward, magnetic reconnection occurs in the magnetosphere s lobe, driving sunward plasma flow in the dayside polar cap. Although Joule heating is often observed at the reconnection footpoint during Bz northward periods, it typically cannot be fully explained by global-scale dynamics. We will use a variety of ground- and space-based instruments to investigate mesoscale (100-500 km) features that may play a role in Joule heating at the ionospheric footpoint of lobe reconnection under IMF Bz north conditions determined by the Advanced Composition Explorer (ACE).
The proposed research addresses the following science questions:
o How much do dayside mesoscale electrodynamic structures driven by lobe reconnection contribute to energy deposition in the polar cap ionosphere and upper thermosphere?
o Does mesoscale precipitation in the polar cap significantly alter the effectiveness of Joule heating at different altitudes and change the total energy deposited?
o How does the neutral wind response to lobe reconnection impact Joule heating in the dayside polar cap and what measurements are necessary to correctly account for this?
The Resolute Bay Incoherent Scatter Radar North (RISR-N) and the Super Dual Auroral Radar Network high-frequency radars at Clyde River, Inuvik, and Rankin Inlet overlap this region in the dayside sector. We will combine line-of-sight plasma velocity measurements from all radars to reconstruct the full 3D mesoscale velocity field. The electric-field and plasma-flow instruments on the Swarm and Defense Meteorological Satellite Program (DMSP) constellations will provide high-resolution plasma velocity measurements when the satellites cross the dayside sector.
The local precipitation spectra will be inverted from RISR-N plasma density and measured directly with the DMSP particle instrument. Strong precipitation modifies conductivity profiles in the upper atmosphere, which may affect Joule heating at different altitudes.
Although neutral dynamics are often disregarded, a strong neutral wind opposing plasma convection is known to substantially increase Joule heating. To investigate this, we will consider the measurements of mesoscale plasma velocity relative to neutral wind dynamics from the Resolute Bay Fabry-Perot Interferometer and global neutral wind models. Plasma temperature enhancements measured by RISR-N will allow us to test if the existing theory can correctly predict observed heating when neutral dynamics are fully accounted for.
This project will make critical progress toward understanding the role of mesoscale sunward convection driven by IMF variations in energy deposition and heating of the ionosphere. The research is directly relevant to Key Science Goal 2 of the Decadal Survey: Determine the dynamics and coupling of Earth s magnetosphere, ionosphere, and atmosphere and their responses to solar and terrestrial inputs. The research is also timely in its relevance to the Geospace Dynamics Constellation Goal 1: Understand how the high latitude ionosphere-thermosphere system responds to variable solar wind/magnetosphere forcing.

Alfred Mallet/University of California, Berkeley
Compressible fluctuations in inertial-range Solar-wind turbulence

Solar wind turbulence consists of fluctuations that span a vast range of spatial scales. On length-scales larger than the ion gyroradius, the turbulence consists of a dominant incompressible Alfvénically polarized component, and a minority compressive population [Klein et al. 2012] whose spectrum tracks that of the Alfvénic fluctuations [Chen et al. 2011]. According to linear theory, the compressive fluctuations should be strongly damped: thus, their presence on all inertial-range scales is somewhat surprising. This project will study the compressive component of the solar wind close to the sun observed by NASA's Parker Solar Probe (PSP), and can be subdivided into three main parts.

The first task will be to measure and theoretically model the statistical properties of the compressive component, including its intermittency, following on from earlier models of Alfvénic-only intermittent turbulence [Mallet et al. 2015, 2017]. This will already be a significant advance in our understanding of collisionless plasma turbulence, a fundamental physical process in the heliosphere and in many other astrophysical settings. Recently, a mechanism has been proposed to explain the lack of damping, the stochastic plasma echo [Schekochihin et al. 2016]: in a strongly turbulent plasma, linear damping of the compressive modes may be suppressed by nonlinear interactions with the turbulent fluctuations. This has been observed in numerical simulations [Meyrand et al. 2019], but not yet in real turbulence. The other parts of the project involve looking for observational signatures of the stochastic echo, as well as theoretical work.

The second part involves the mode structure of the compressive fluctuations. Although the solar wind is nearly collisionless, the compressive fluctuations have polarization more similar to the MHD (collisional) slow mode than to the collisionless mode [Verscharen et al. 2017]. This could be due to the stochastic echo suppressing the damping, with the side effect that the polarization adjusts. We will study this problem theoretically, solving the coupled equations for the polarization in the presence of the stochastic echo, and testing the model using measurements of the turbulence from PSP. This measurement only requires knowledge of the plasma density, velocity and temperature, and the magnetic field, on inertial range timescales.

The final part of the project studies fine structure in the ion velocity distribution function (VDF). Schekochihin et al. 2016 used a spectral (Hermite-moment) representation of the perturbed VDF, showing that while a linearly damping mode has a shallow spectrum, the stochastic echo results in a steep spectrum. The formalism used relies on the assumption that the background VDF is Maxwellian - not the case in the solar wind. Thus, the theory needs to be extended to more realistic VDFs, developing predictions for the scaling properties of their fluctuations, and finally compared with real data from PSP.

Our proposed project will characterise and explain the compressive component of the solar wind turbulence, an important physical process which affects the thermodynamic background upon which all other heliospheric physics occurs. Looking for the stochastic echo in these compressive inertial-range fluctuations is very observationally accessible, since it only requires measurements of the ion VDF on long inertial-range timescales (between 10s and 1000s).

Finally, it is worth pointing out that the stochastic echo may occur much more generally than in this situation; for example, in the small-scale dissipation range turbulence in the solar wind, as well as in fusion and astrophysical plasmas. Thus, observational confirmation would dramatically alter our picture of the physical process of turbulent heating in many other plasmas throughout the universe.

Ryan McGranaghan/Atmospheric & Space Technology Research Associates
Understanding the high-latitude geospace system to the point of prediction: The Heliophysics KNOWledge Network (Helio-KNOW)

The complexity and variability of the solar wind-magnetosphere-ionosphere (SWMI) system, particularly the auroral high latitudes, represents a pressing challenge to the fundamental understanding of the Heliophysics system. Among the most important and yet uncertain aspects of the SWMI system is energy and momentum coupling between regions, which is accomplished by electromagnetic fields, or Poynting Flux (PF), and the transfer of charged particles.

SWMI coupling research to date has not fully utilized datasets that cover the wide gamut of drivers and ionospheric responses and only led to rudimentary tools that make the diverse data more usable. To optimally prepare for future missions such as the Geospace Dynamics Constellation, the next five years are critical to improve our scientific understanding of SWMI phenomena and to develop the necessary tools to realize the scientific potential of the array of current and future datasets. The next leap forward in our understanding requires the utilization of richly diverse datasets, in terms of the physical parameters, location, and spatiotemporal scales.

Therefore, the central challenge that this proposal seeks to address is information flow through physical processes in the SWMI system and the extent to which mesoscale particle precipitation, ion outflow, and PF are sensors of that information. The challenge requires the Heliophysics KNOWledge Network (Helio-KNOW), a new and possibly disruptive data analytic approach for a system-level understanding and prediction of MI coupling phenomena, applicable to our diverse multi-point, multi-parameter, sparsely-sampled SWMI datasets. The investigation is organized by the following Science Questions (SQs):
SQ1: To what extent can new representations increase the information content of SWMI data and thereby reduce the uncertainties in models of the system?
SQ2: What are the characteristic temporal relationships between the solar wind and energy and momentum transport between the magnetosphere and ionosphere and how do they vary by region and spatial scale?
SQ3: What are the repeatable ways that mesoscale spatial scales (100s km) depart from existing large-scale understanding and what is the significance of the departures?

Improved understanding of the SWMI system depends on improved information representation (linking data and improving functional representations). It is now possible to utilize multi-domain data with fewer limitations in scale, resolution, and model sophistication to discover multiscale (including cross-scale) linkages that previously would not have been apparent and to lower barriers to rigorous use of those data. The proposed research will cut across disciplinary lines to produce new linked, or network, representations of SWMI data from the NASA Heliospheric Observational System (HSO) that better utilize their information content to understand to the point of prediction energy and momentum transfer between the magnetosphere and ionosphere.

This proposal is highly relevant to specific objectives of NASA programs, directly responding to three Heliospheric community-wide imperatives:
1.Heliospheric Research Program overarching objective: Understand the Sun and interactions with the Earth, including space weather, and the specific objective to Advance our understanding of the connections between solar variability and Earth space environment;
2.Solar and Space Physics Decadal Survey Key Science Goal 2: "Determine the dynamics and coupling of Earth s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs and the sub-goal to understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing across scales; and
3.The four cross-cutting priorities identified by the NASA 2020-2024 Science Plan, namely the creation of revolutionary scientific discovery through a focus on innovation, experimentation, and cross-disciplinary research.

Adam Michael/Johns Hopkins University
Particle Transport and Energization in the Magnetotail Transition Region

Science goals and objectives
The the formation and build up of the ring current, one of the most important current system affecting geospace, remains a major unsolved problem of magnetospheric physics. Ongoing work has shown that the transition region (typically ~8-20 RE from Earth) is crucial to addressing this problem. This region not only delivers energy to the inner magnetosphere but the complex processes within, heat and accelerate the particles which form the ring current, one of the most important current systems affecting geospace. Our primary goal is to develop a comprehensive, quantitative physical description for ion transport and energization through the magnetotail transition region.

Characterizing this region has been a daunting challenge for both in situ measurements and global simulations due to the cospatial, multi-scale nature of the problem, which involves large scale convection, azimuthally localized fast bursty bulk flows, and energy-dependent drifts that transport and accelerate the plasma. While observational and simulation efforts have their shortcomings, when combined, multipoint observations and global, multi-scale models provide a powerful tool to investigate this poorly understood region. We will describe the physical processes critical to the build up of the ring current through addressing the following science questions:
1. What are the roles of the mesoscale flows and field structures in the transport and energization of ions through the transition region?
2. To what degree are these processes adiabatic for particles of different species and energy?

3. How much energy density is carried by the non-thermal ions through the transition region?

Methodology

We will develop a large data set of earthward plasma sheet flows by combining multipoint observations from Geotail, Cluster, MMS, and THEMIS measurements. We will also deploy a global, multi-scale magnetospheric model along with test particle simulations, each capable of resolving structures critical to understanding transport through the transition region. We will organize our study over periods of varying geomagnetic activity. These tools will enable addressing these compelling science questions through the following approach.

Statistical role of mesoscale flows: We will derive the statistical properties of the processes within the transition region through cross-scale data-model comparison to determine the large-scale occurrence and characteristics of the mesoscale flows and the dominant transport and acceleration processes of the ions.

Targeted event studies: We will perform focused investigations through multi-point measurements and high-resolution simulations to determine particle evolution within these mesoscale flows. Knowledge of the 3D trajectories and evolution within BBFs and near DFs will provide vital information to contextualize and interpret the observations.

Novel treatment of the transition region: We will develop a novel physical treatment of the transition region that incorporates the non-adiabatic ion flux into the inner magnetosphere.

Relevance to objectives

This work contributes to NASA s Heliophysics' overarching goal and all three primary science objectives. The characterization of the transition region will identify the dominant transport and acceleration mechanisms occurring in a critical region for understanding the buildup of the ring current and radiation belts (Objective #1). Spanning a range of geomagnetic conditions will allow us to correlate the location and importance of these processes to activity level (Objective #2). The ring current is one of the most important current systems affecting geospace, therefore understanding its source is crucial to the overall response of the magnetosphere to solar driving (Objective #3).

Jamie Rankin/Princeton University

Connecting In-Situ and Global Responses in the Heliosheath and Very Local Interstellar Medium

For the last 7 years, Voyager 1 has made measurements in the previously unexplored Very Local Interstellar Medium (VLISM), leading to many intriguing observations and discoveries about how the Sun influences its surroundings. In-situ phenomena, including electron plasma oscillations, energetic particle enhancements, weak, laminar shocks, and mysterious galactic cosmic ray anisotropies confirm the long-accepted idea that solar events can coalesce into larger structures that traverse the heliosphere, perturb the heliopause, and influence the VLISM. For 6 of those years, Voyager 2 was concurrently making its way through the outer heliosheath, providing an unprecedented opportunity to compare data with its twin to examine these very different plasma environments. Meanwhile, IBEX has now taken 11 years of data, and, amongst its many discoveries, continues to measure the heliosphere s time-delayed global response to a dramatic increase in solar wind (SW) dynamic pressure that occurred in late-2014 (the effects of which have also been seen by Voyager 1). While both spacecraft observe VLISM phenomena in complementary ways, Voyager s in-situ observations and IBEX s global measurements have historically been studied independently. In this proposal, I will connect these complementary datasets to provide even greater insights about the Sun and its surroundings. I will analyze in-situ energetic particle, magnetic field, and plasma responses to solar transient events and SW dynamic pressure changes to characterize how local and global phenomena influence the heliosphere s interactions with the VLISM, thereby laying the foundations for multi-instrument, multi-spacecraft efforts in order to better understand both in-situ and global observations as a whole.

I will examine in-situ disturbances in the SW and VLISM and link these results to global observations via the following science questions:
1. What physical processes are responsible for the formation and behavior of energetic particle intensity enhancements in the VLISM and how do these relate to other transient events (e.g. magnetic compressions/rarefactions, electron plasma oscillations, and galactic cosmic ray anisotropies)?
2. What does the time-delayed, in-situ response to changes in SW dynamic pressure reveal about the heliosheath and VLISM and how does it compare to global effects?
3. What governs in-situ and global responses to periods of plasma compression and expansion in the heliosheath, and how do these compare in the VLISM?

Specifically, I will analyze Voyager 1 & 2 observations from 2008 through Aug-2020, using publicly-available data from all working instruments: CRS, LECP, MAG, PLS, and PWS. This multi-instrument analysis will rely on framework developed by Rankin (2019; Caltech PhD dissertation), Rankin et al. (2019a), Rankin et al. (2019b), and Rankin et al. (2020). In-situ responses will be quantified, including: (a) plasma densities, temperatures and pressures, (b) magnetic field magnitudes and directions, and (c) energetic particle intensities and spectra. Resulting responses and their temporal evolution will be investigated via comparative analysis. Well-known analytical functions will be fitted to observations to characterize fundamental physical processes. To the extent possible, in-situ results will be evaluated in light of IBEX s global ENA observations, which are publicly-available and detailed in the literature. By examining in-situ disturbances in the SW and VLISM, this investigation ultimately aims to connect these findings from Voyager s Interstellar Mission to IBEX s global observations, and thereby addresses two high-level science goals of the Heliophysics Decadal Survey: (3b) Determine the interaction of the Sun with the interstellar medium and (4) Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Daniel Vech/University Of Colorado, Boulder

Comparison of Kinetic Alfvén and Whistler Turbulence in Space Plasmas with a Robust Wave Mode Identification Technique

Science Goals and Objectives:
On scales smaller than the proton gyroradius, two types of electromagnetic turbulence can occur in space plasmas: kinetic Alfvén (KAW) turbulence and whistler turbulence. Identifying the type of fluctuations is central to understanding the dissipation of turbulent energy in a whole range of plasma systems such as solar corona, solar wind, and magnetosphere. Previous attempts to distinguish between KAW and whistler turbulence either led to uncertain conclusions or relied on data products, which were available for short intervals only. The high cadence data from the Magnetospheric Multiscale Mission (MMS) makes it possible to use an innovative and robust technique to conclusively identify intervals with either type of fluctuations. The correlation between high frequency (> 1 Hz) plasma density and parallel magnetic fluctuations is a simple proxy to distinguish between the two types of fluctuations: in KAW turbulence this is a negative correlation, while it is positive in whistler turbulence. The available MMS burst data set has become large enough that it now provides us with a wealth of available measurements to make a detailed comparison between intervals with KAW and whistler turbulence in Earth s magnetosphere.

We will answer the following specific science questions (SQ):
SQ1: Under what plasma conditions do KAWs and whistlers deviate from linear theory?
SQ2: Does the anisotropy of magnetic fluctuations allow the formation of kinetic scale current sheets in either KAW or whistler turbulence?
SQ3: Does the damping of KAWs and whistlers lead to anomalous scaling of ion, electron velocity and magnetic fluctuations?

We will use the entire available burst mode database of MMS (2015-2020) including the Fast Plasma Instrument s (FPI) ion and electron velocity distribution functions (150 ms and 30 ms cadence, respectively) in conjunction with the magnetic field measurements. We will use the FPI and fluxgate magnetometer data to identify the background plasma parameters such as plasma beta, magnetic turbulence amplitude and wave mode of kinetic scale turbulence.

Methodology:
In SQ1 we will use k-filtering technique to obtain experimental dispersion relations of KAWs and whistlers. We will quantify how the non-Maxwellian features, magnetic turbulence amplitude and wave propagation direction (with respect to the background magnetic field) cause deviations in the experimental dispersion relations from the predictions of linear wave theory.

SQ2: We will study the 3-D structure of magnetic fluctuations to understand whether the kinetic scale eddies resemble to current-sheet like structures, which are important for the dissipation of turbulent energy.

SQ3: We will study the scaling of the 1st-6th order structure functions of ion and electron velocity and magnetic fluctuations and reveal whether the energy of those fluctuations are passively advected in kinetic scales or they show signatures of anomalous scaling suggesting that they are significantly affected by the damping process.

Relevance:
KAWs and whistler waves are abundant in the plasma Universe where they play a key role in heating of space plasmas, energy input into Earth s auroral regions, particle outflow and atmospheric loss and they have implications for laboratory plasmas as well. Despite their fundamental role in a wide range of physical processes, the properties of these wave modes are still poorly understood since conclusive wave mode identification with previous spacecrafts was difficult. The proposed work is therefore critical to NASA and its Heliophysics Decadal Survey Goal #4 Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe . This proposed work will enhance the science return of the MMS mission and, by characterizing KAWs and whistlers, goes beyond the original mission goals.

Jongsoo Yoo/Princeton University

Understanding the role of lower hybrid drift waves in electron heating and the onset of fast reconnection

Magnetic reconnection is one of fundamental processes dominating the dynamics of heliophysical plasmas from the solar surface to the interface between heliosphere and local galactic plasma. Despite the known importance of reconnection in explosive events such as solar flares, there still exist a number of outstanding critical questions. These questions include the required dissipation for fast reconnection and the underlying mechanisms for its sudden onset.

Lower hybrid drift waves (LHDWs) have been frequently observed in both space and laboratory but the precise role of LHDWs in magnetic reconnection is still unclear, mostly due to the limited diagnostic capability in space. In this proposal, motivated by space observations, a series of well-diagnosed laboratory experiments will be used, in conjunction with theory and numerical simulations, to investigate the role of LHDW in electron heating in the electron diffusion region (EDR) and the onset of fast reconnection.

Electron heating is related to a crucial remaining problem in reconnection research, namely how magnetic energy is dissipated in the EDR. The onset of fast reconnection is related to the most important application of reconnection research, which is the prediction of space weather. Here we address the role of LHDWs in these two important problems. The primary objectives are:
(1) To quantitatively determine the contribution from LHDWs in electron heating,
(2) To investigate the excitation of LHDWs during the onset of fast reconnection and the possible role of LHDWs in fast reconnection.

To achieve these objectives, we have identified 10 events from the Magnetospheric Multiscale mission with LHDW activity. Data from these events will be the guideline of laboratory experiments, linear and quasi-linear analyses, and numerical simulations. In particular, laboratory experiments will be conducted to have similar key dimensionless parameters such as plasma beta. Moreover, we will validate our local theoretical model with data from these events. In addition, profiles from these events will be used to set up initial conditions for particle-in-cell (PIC) simulations.

Laboratory experiments will be performed in the Magnetic Reconnection Experiment (MRX) and Facility for Laboratory Reconnection Experiments (FLARE) at the Princeton Plasma Physics Laboratory (PPPL). In particular, we will observe LHDW activity with high-frequency fluctuation probes under various parameters such as electron beta, guide field strength, and the amount of asymmetry. By quasi-linear analyses with measured amplitudes, we will estimate LHDW-driven anomalous terms including heat generation via the wave-particle interaction to understand electron heating by LHDWs. For the onset of fast reconnection, we plan to initiate fast reconnection by activating an internal set of coils, which increases an initially low reconnection rate. We will monitor the evolution of the current sheet structure responding to the large external reconnection drive. At the same time, we will observe how LHDWs are excited during the onset of fast reconnection and will quantify contribution of LHDWs to fast reconnection.

For detailed nonlinear wave-particle interactions and kinetic processes, we will perform 3D PIC simulations. The evolution of LHDWs and electron temperature during the onset of reconnection will be examined. We will quantify the contribution from LHDWs to anomalous resistivity and viscosity, which will be compared to estimates from linear and quasi-linear analyses.

Achievement of the proposed objectives will advance the current understanding of microscale physics during reconnection. This proposed research will be the first detailed quantitative study of wave-particle interactions in the EDR. We will be also able to provide inputs for future NASA missions in Earth's magnetosphere on how to improve measurements associated with wave-particle interactions and wave-driven anomalous terms.
