Module 11.1: Reference Document

The [Planetary Science and Astrobiology 2023-2032 Decadal Strategy & Survey] is a large document, and to mitigate any confusion and avoid possible rabbit holes, we have provided you with useful sections from the Decadal Survey to reference during your exploration of Module 11.1 : Choosing a Science Case.

The Summary of the Survey

Below is a cropped version of the Summary from the Decadal Survey. Feel free to use the open spaces as room for notes from you and your team.

Summary

This report of the Committee on the Planetary Science and Astrobiology Decadal Survey of the National Academies of Sciences, Engineering, and Medicine identifies a research strategy to maximize advancement of planetary science, astrobiology, and planetary defense in the 2023-2032 decade. Federal investment in these activities occurs primarily through NASA's Planetary Science Division (PSD); important activities are also conducted by the National Science Foundation (NSF). The decadal committee evaluated potential activities by their capacity to address the priority science questions identified by the committee (Table S.1), cost and technical readiness as assessed through independent evaluation, programmatic balance, and other factors. This summary highlights the committee's top findings and recommendations.

TABLE S.1 The Twelve Priority Science Question Topics

Scientific Themes	Priority Science Question Topics and Descriptions
A) Origins	Q1. *Evolution of the protoplanetary disk.* What were the initial conditions in the solar system? What processes led to the production of planetary building blocks, and what was the nature and evolution of these materials?
	Q2. *Accretion in the outer solar system.* How and when did the giant planets and their satellite systems originate, and did their orbits migrate early in their history? How and when did dwarf planets and cometary bodies orbiting beyond the giant planets form, and how were they affected by the early evolution of the solar system?
	Q3. *Origin of Earth and inner solar system bodies.* How and when did the terrestrial planets, their moons, and the asteroids accrete, and what processes determined their initial properties? To what extent were outer solar system materials incorporated?
B) Worlds and Processes	Q4. *Impacts and dynamics.* How has the population of solar system bodies changed through time, and how has bombardment varied across the solar system? How have collisions affected the evolution of planetary bodies?
	Q5. *Solid body interiors and surfaces.* How do the interiors of solid bodies evolve, and how is this evolution recorded in a body's physical and chemical properties? How are solid surfaces shaped by subsurface, surface, and external processes?
	Q6. *Solid body atmospheres, exospheres, magnetospheres, and climate evolution.* What establishes the properties and dynamics of solid body atmospheres and exospheres, and what governs material loss to space and exchange between the atmosphere and the surface and interior? Why did planetary climates evolve to their current varied states?
	Q7. *Giant planet structure and evolution.* What processes influence the structure, evolution, and dynamics of giant planet interiors, atmospheres, and magnetospheres?
	Q8. *Circumplanetary systems.* What processes and interactions establish the diverse properties of satellite and ring systems, and how do these systems interact with the host planet and the external environment?
C) Life and Habitability	Q9. *Insights from terrestrial life.* What conditions and processes led to the emergence and evolution of life on Earth, what is the range of possible metabolisms in the surface, subsurface and/or atmosphere, and how can this inform our understanding of the likelihood of life elsewhere?
	Q10. *Dynamic habitability.* Where in the solar system do potentially habitable environments exist, what processes led to their formation, and how do planetary environments and habitable conditions co-evolve over time?
	Q11. *Search for life elsewhere.* Is there evidence of past or present life in the solar system beyond Earth and how do we detect it?
Cross-cutting A-C linkage	Q12. *Exoplanets.* What does our planetary system and its circumplanetary systems of satellites and rings reveal about exoplanetary systems, and what can circumstellar disks and exoplanetary systems teach us about the solar system?

Together, the SoP findings and recommendations aim to assist NASA's PSD in boldly addressing issues that concern its most important resource: the people who propel its planetary science and exploration missions.

MISSION CLASSES, BALANCE, AND ONGOING ACTIVITIES

The committee's statement of task (Appendix A) defines missions in three cost classes—small, medium, and large. The Discovery program supports small, principal-investigator (PI)-led missions that address focused science objectives with a high launch cadence. Medium-class New Frontiers missions are PI-led and address broader science goals. Large ("Flagship") missions address broad, high-priority science

Recommendation: NASA should maintain the Mars Exploration Program, managed within the PSD, that is focused on the scientific exploration of Mars. The program should develop and execute a comprehensive architecture of missions, partnerships, and technology development to enable continued scientific discovery at Mars.

Recommendation: Subsequent to the peak-spending phase of Mars Sample Return, the next priority medium-class mission for the Mars Exploration Program should be Mars Life Explorer. (Chapter 22)

LUNAR DISCOVERY AND EXPLORATION PROGRAM

The Lunar Discovery and Exploration Program (LDEP) supports industry partnerships and innovative approaches to accomplishing exploration and science goals, including the Commercial Lunar Payload Services (CLPS) program for lunar landing services. LDEP is funded within PSD, but budgetary responsibility is split between PSD and the Exploration Science Strategy and Integration Office (ESSIO). No single organizational chain has authority for executing lunar science and missions; as a result, LDEP activities are currently not optimized to accomplish high-priority science. A structured, science-led approach to setting goals and measurement objectives for the Moon is needed for LDEP and to provide scientific requirements for Artemis.

Recommendation: The Planetary Science Division should execute a strategic program to accomplish planetary science objectives for the Moon, with an organizational structure that aligns responsibility, authority, and accountability. (Chapter 22)

Recommendation: The advancement of high-priority lunar science objectives, as defined by the Planetary Science Division based on inputs from this report and groups representing the scientific community, should be a key requirement of the Artemis human exploration program. Design and implementation of an integrated plan responsive to both NASA's human exploration and science directorates, with separately appropriated funding lines, presents management challenges; however, overcoming these is strongly justified by the value of human-scientific and human-robotic partnerships to the agency and the nation. (Chapter 22)

The committee prioritizes the medium-class Endurance-A lunar rover mission (*Appendix C*). Endurance-A will traverse diverse terrains in the South Pole Aiken (SPA) basin, collect ~100 kg of samples, and deliver the samples to a location for return to Earth by astronauts. Endurance-A will address the highest priority lunar science, revolutionizing our understanding of the Moon and the early history of the solar system recorded in its most ancient impact basin. Return of Endurance-A samples by Artemis astronauts is the ideal synergy between NASA's human and scientific exploration of the Moon, producing flagship-level science at a fraction of the cost to PSD through coordination with Artemis.

Recommendation: Endurance-A should be implemented as a strategic medium-class mission as the highest priority of the Lunar Discovery and Exploration Program. Endurance-A would utilize Commercial Lunar Payload Services to deliver the rover to the Moon, a long-range traverse to collect a substantial mass of high-value samples, and astronauts to return them to Earth. (Chapter 22)

RESEARCH AND ANALYSIS

Robotic solar system exploration is driven by the desire to increase knowledge. Strong, steady investment in research and analysis (R&A) is needed to ensure (1) maximal return from mission data; (2)

that data drives improved understanding and novel, testable hypotheses; (3) that advances feed into future mission development; and (4) training a diverse workforce. The fraction of PSD's budget devoted to R&A has decreased from 14 percent in 2010 to a projected 7.7 percent by FY23. It is essential to the nation's planetary science efforts that this trend be reversed. The openly competed R&A programs drive innovation, provide rapid response to new discoveries, identify the most meritorious ideas, and attract new and increasingly diverse investigators.

> **Recommendation: The Planetary Science Division (PSD) should increase its investment in research and analysis (R&A) activities to achieve a minimum annual funding level of 10 percent of the PSD total annual budget. This increase should be achieved through a progressive ramp-up in funding allocated to the openly competed R&A programs, as defined in this decadal survey. Mid-decade, NASA should work with an appropriately constituted independent group to assess progress in achieving this recommended funding level.** (Chapters 17 and 22)

Planetary Body : The Moon

This section from the Survey goes through all science regarding the Moon on a broad scale crucial because the impact event defined the initial condition of Earth. Moreover, the Moon-forming impact was likely the last catastrophic event in the inner solar system, and therefore it also defined the end of the accretion phase. In summary, the timing of the Moon's origin remains an open question.

Further insight into the Moon's formation and thermochemical evolution has been gained over the past decade from intense study of its inventory of indigenous volatile elements. Whereas all terrestrial planetary bodies are depleted in volatile elements relative to CI chondrites and the Sun's photosphere, the Moon's depletion is more extreme and results from a combination of the cataclysmic circumstances under which it is thought to have formed, the geochemical signature of the protoplanet impactor, and/or the process of planetary differentiation. However, while the Moon was once thought to contain less than one part per billion H_2O in its interior, new measurements show that at least some portions of the mantle contain hundreds of parts per million H_2O, and remote detection of hydrated materials in some uplifted crustal materials further attest that the Moon is far from "bone dry". The discovery that stable isotope compositions of moderately volatile and volatile elements in lunar samples are fractionated relative to terrestrial values further suggests that the Moon lost a substantial fraction of its volatile elements both during and after it formed. Volatile loss from the lunar interior was likely important for generating transient atmospheres and for distributing some of the volatile species presently on the lunar surface.

Major advances in our understanding of the interior and crustal structure of the Moon and its bulk composition have come from new ultra-high-resolution gravity and topography measurements obtained by GRAIL and LRO, respectively. These data, when combined with Apollo seismic constraints, indicate the lunar crust has high porosity and a mean thickness of 34-to-43 km, with an average crustal thickness of ~55 km on the farside and ~30 km on the nearside (Figure 2.4).

Such large-scale crustal asymmetry is further found in nearside/farside differences in porosity, heat-producing elements, and extent of volcanism; the cause of the Moon's crustal asymmetry remains one of the greatest outstanding mysteries regarding lunar early evolution. The crustal thickness estimates also provide constraints on the bulk composition of the silicate portion of the Moon. In particular, the crustal thickness estimates indicate the Moon has a complement of refractory elements that is a close match to the bulk silicate composition of Earth rather than earlier estimates, based on inferred crustal thickness larger than currently accepted values that indicated the Moon was enriched in refractory elements by up to 50 percent relative to Earth and CI chondrites. GRAIL data, coupled with advances in theoretical models, have also transformed our understanding of how large impact basins (and the associated, mysterious "mascons" that destabilized the orbits of early lunar missions) formed, and how tides shaped the Moon. New insights have been gained into the Moon's deep interior structure as well, from a combination of data from GRAIL and LRO, modern analyses of Apollo seismic data, and continued laser ranging observations, and indicate that the Moon likely has a solid inner core between 130-and-200 km in radius, possibly overlain by a fluid outer core extending out to ~380 km in radius.

Over the past decade, remanent crustal magnetism studies and laboratory analyses of returned lunar samples have revealed that the ancient Moon had an internally generated magnetic field. Between 4.25 and 3.56 Ga, surface field intensities reached values up to 40-110 µT. This high-field period was followed by a lower intensity field of ~5 µT or less that may have persisted beyond 2 Ga. However, no single proposed dynamo mechanism to date satisfactorily explains both the longevity and intensity of the ancient lunar dynamo inferred from the paleomagnetic record. However, ongoing research is further exploring hypotheses such as a basal magma ocean dynamo, the possibility that impact effects could have led to transient amplification of a baseline core dynamo field, or a situation wherein multiple dynamo mechanisms with differing predicted field intensities may have operated at different points in time.

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FIGURE 2.4 Large-scale crustal asymmetries on the Moon. A, Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA) albedo map of the Moon at 1064 nm (Lemelin et al. 2016). B, High resolution lunar topography, derived from the combination of LRO/LOLA and SELENE Terrain Camera data (Barker et al. 2015). C, Thorium abundance derived from the Lunar Prospector Gamma-Ray Spectrometer (Lawrence et al. 2007). D, Model for the crustal thickness of the Moon, derived from the Gravity Recovery and Interior Laboratory (GRAIL) mission and LRO/LOLA (Wieczorek et al. 2013, Goossens et al. 2019). E, Bouguer gravity anomaly (gravity anomaly corrected for surface topography) derived from GRAIL and LRO/LOLA (Zuber et al. 2013, Goossens et al. 2019). F, Bouguer gravity gradient (a measure of the horizontal derivative of the Bouguer gravity anomaly) derived from GRAIL and LRO/LOLA (Andrews-Hanna et al. 2014). Figure created by James Tuttle Keane.

The Moon's dominant form of volcanism involved eruption of voluminous basin-filling mare lavas peaking about 3-to-3.5 Ga, but samples recently returned from Oceanus Procellarum by the Chang'e 5 mission show that the formation of flood basalts continued until at least 2 Ga. Morphological and compositional diversity is expressed through abundant mafic pyroclastic deposits, less common silicic pyroclastics, and complexes of small domes and cones and evidence for large-scale shields. Over the past decade, new evidence challenges the notion that all lunar volcanism is ancient. The Lunar Reconnaissance Orbiter Camera (LROC) revealed numerous irregular mare patches, depressions containing patchy rough and smooth mafic deposits (Figure 2.5), thought to be remnants of eruptions younger than 100 My, volcanic materials resurfaced by late degassing, or the product of more ancient eruptions that resulted in materials with atypical physical properties. If these features are confirmed to be related to recent eruptions, the occurrence of such young volcanism implies that the lunar mantle was warmer than previously thought, and/or that heterogeneous or localized concentrations of radioactive elements allowed for small-scale eruptions to continue late into lunar evolution. In addition, silicic volcanism appears to be more prevalent than previously appreciated, raising the question of how substantial volumes of evolved magma could be produced on a single-plate planetary body.

GRAIL and LRO data enabled a new global inventory of magmatic intrusions, suggesting that for every volcanic eruption at the surface, there is an order-of-magnitude more magmatism beneath the surface. Analyses of the Moon's Bouguer gravity revealed a global population of previously unseen, 100-km long igneous bodies distributed across the Moon, likely reflecting a period of global expansion and magmatism early in the Moon's history. On the nearside, even larger dikes and buried rifts were discovered enclosing the Procellarum KREEP Terrane (PKT; a region characterized by low elevations, thin crusts, extensive mare basalts, and abundant heat-producing elements), delineated by a 3.5-ppm-Th contour on the lunar nearside hemisphere. The buried rifts enclosing the PKT may be the result of planetary-scale tectonism and magmatism, and may have been the plumbing for much of the mare basalts that preferentially flooded the lunar nearside terranes. This early period of expansion was succeeded by a period of global contraction as a result of secular cooling. Evidence for this contraction comes from LROC images, which revealed a far greater abundance of contractional tectonic features than previously known, particularly lobate scarps. Similar to those on Mercury, but generally of smaller scale, these features are the surface expression of thrust faults, and their locations suggest that they have been further influenced by stresses from tidal interactions with Earth and from orbital recession away from Earth. Movement along these faults may continue into the present day, and may be the source of the large but rare shallow moonquakes recorded by Apollo seismometers.

The well-preserved state and ancient surface of the Moon has exquisitely preserved the most complete record of the stellar events that have occurred in our part of the solar system since the formation of the Earth-Moon system. Although the early record of the accretion and rate of exogeneous delivery of chemical compounds are poorly preserved on Earth, the flux of chemical inventories important to the emergence and subsequent evolution of Earth's life omay be decipherable at the Moon. The Moon's impact history not only provides a means to understand the linked evolution of the Earth-Moon system since antiquity, but also the chronology of events across the solar system. Indeed, significant advances have been made in the past decade by refined laboratory analysis of samples that have been returned and dated from the Moon's surface. An example of such a recent advance is an improved age determination for the important nearside impact basin Imbrium to 3.91-to-3.94 Ga based on U-Pb dating. The history of impacts on the Moon prior to Imbrium remains a subject of substantial uncertainty. Since the 1970s, it has been hypothesized that there was an intensive peak in the impact bombardment of the Moon in the 3.8-4.1 Ga epoch (known as the Late Heavy Bombardment or lunar cataclysm). Modeling and geochemical studies completed over the previous decade have cast doubt on whether an intense impact cataclysm in this epoch is required, in part because the Imbrium impact event may be radically overrepresented in the existing sample collection. At a minimum, the magnitude of the peak in the impact bombardment during this period might be lower than was once thought. GRAIL and LRO substantially clarified the total number of impact basins whose signatures are preserved on the Moon, but the period over which these basins formed remains to be established. Intense interest in the population and ages of lunar basins persists because they have implications beyond the Moon; an intense period of impact bombardment of the lunar surface would be mirrored across the inner solar system, including on the early Earth. Only the most recent impact events are preserved on Earth, and LRO data combined with the terrestrial evidence suggest that the flux of impactors to the Earth-Moon system may have increased at about 290 Ma, and the breakup of specific asteroid families may be recorded in the Moon's crater population.

The last decade has seen a major advance in direct observations of the ongoing impact process on the Moon. In particular, repeat meter-scale imaging by LROC enabled detection of ~500 impact craters formed over the first 11 years of the LRO mission (Figure 2.6). These observations provide a direct constraint on the flux of small meteoroids to the Moon. Terrestrial ground-based monitoring of the Moon has also captured impact flashes associated with impacts, and direct observations of the dusty ejecta from small impacts seen by LADEE. Integrating these observations has led to a revised picture of the rate at which the uppermost surface of the Moon is gardened, and emphasized the importance of high frequency, small meteoroid impacts and their ejecta for gradually eroding surface topography and transporting materials vertically and laterally.

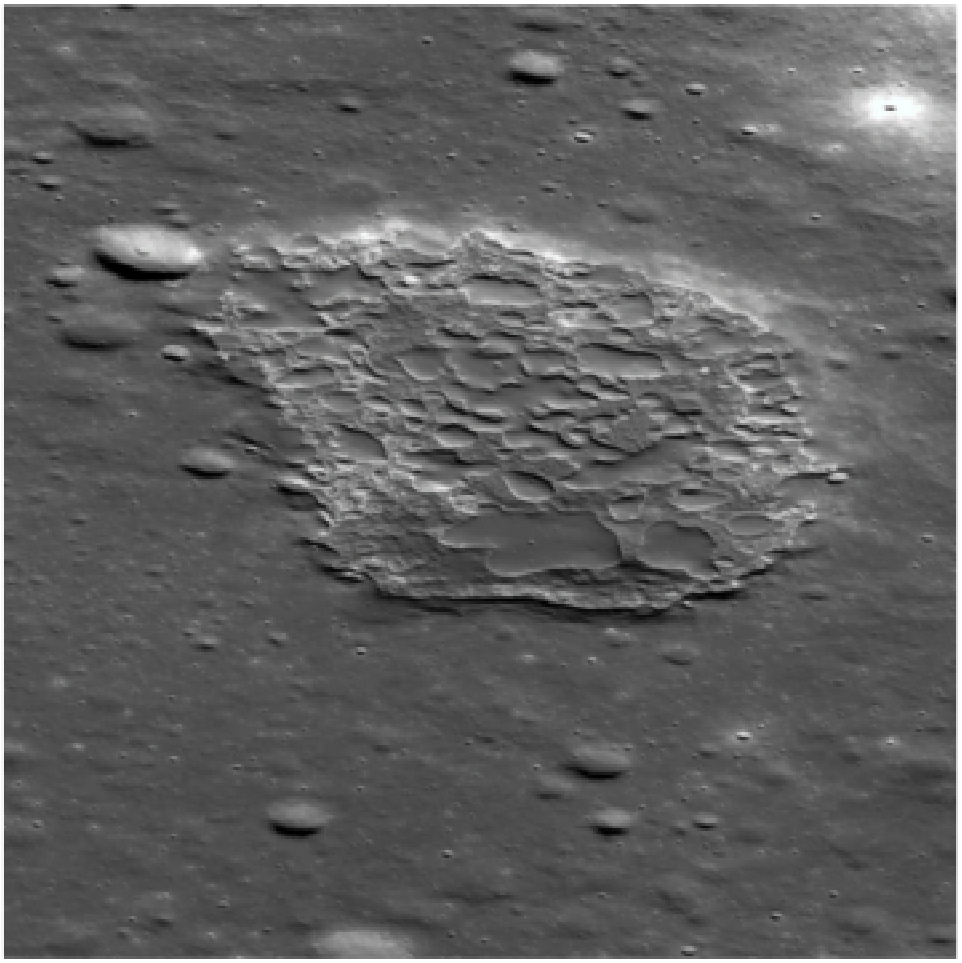

FIGURE 2.5 Possible young volcanism. Oblique view of Ina. The floor of the depression is about 50 m below the surrounding plains and is about 2 km wide from left-to-right (S to N). View from east-to-west, north is to the right, NAC M1108203502LR [NASA/GSFC/Arizona State University].

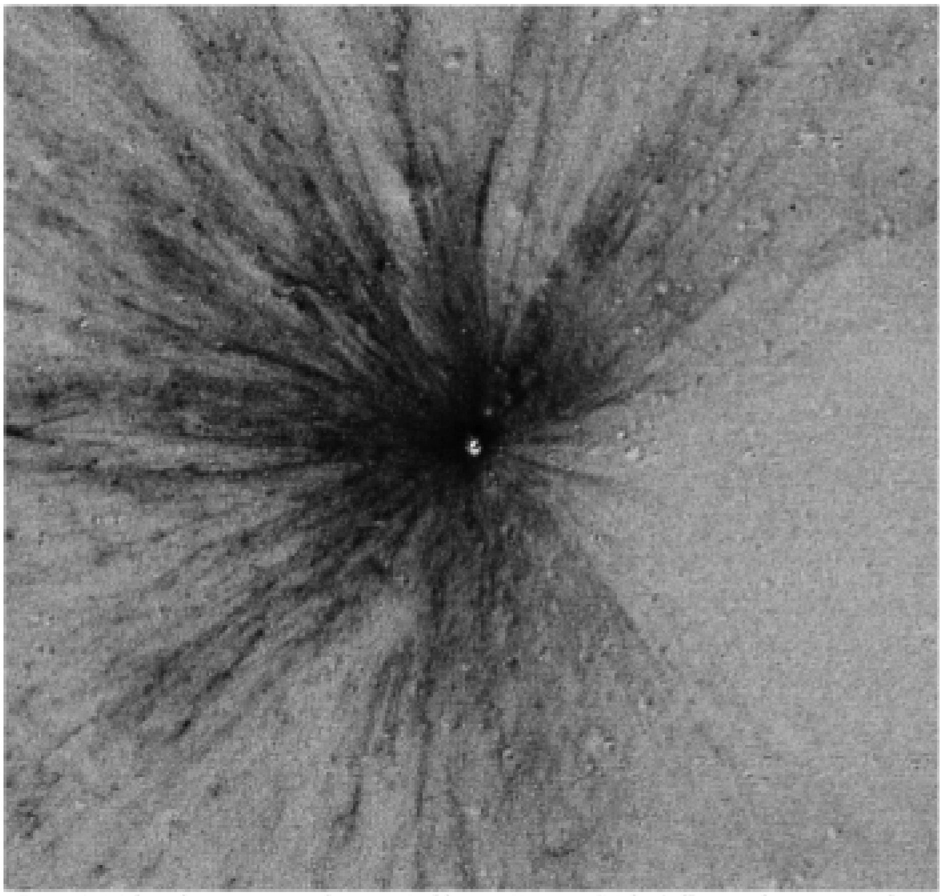

FIGURE 2.6 A brand new crater on the Moon! This new 12 meter (39 foot) diameter impact crater formed between 25 October 2012 and 21 April 2013 and was discovered in a temporal ratio image (after/before) created from two Narrow Angle Camera (NAC) images. Scene is 1200 meters wide (before image: M1105837846R, after image: M1121160416R) [NASA/GSFC/Arizona State University]

Intense interest has also focused attention over the past decade on furthering our knowledge of the abundance, distribution, and origin of the Moon's near-surface volatiles and understanding their implications for where habitable environments may exist in the solar system. LRO data continues to unravel the mysteries of polar volatiles (Figure 2.7), as neutron absorption measurements provide increased detail regarding the distribution of hydrogen, and far-ultraviolet and laser reflectometry data are consistent with surface frosts in polar shadowed regions. Whereas previous data were ambiguous as to the form in which hydrogen is present, results from Moon Mineralogy Mapper data confirm for the first time that at least some polar H is present as H_2O. Numerical modeling indicates that volatiles are also thermodynamically stable beneath the surface in areas of temporary sunlight near the lunar poles, and in micro-cold traps at higher latitudes where small shadows persist. New measurements from the Stratospheric Observatory for Infrared Astronomy (SOFIA) indicate that H_2O is present in near-surface sunlit regions, likely derived from solar wind H^+ and stored within impact glasses known as agglutinates or possibly between regolith grains. Offsets in the distribution of hydrogen from the poles have been interpreted to suggest that the location of the poles may have changed over time due to large impacts and/or volcanism that affected the Moon's obliquity, and thus some portion of the Moon's polar volatiles are preserved from those ancient times and recorded volatile delivery from various sources such as comets, asteroids, solar wind implantation, and/or volcanic outgassing. Through such interrelated processes, the distribution and nature of polar volatile deposits may be indicative of the geologic and geophysical evolution of the Moon as well as the bombardment history of the inner solar system.

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FIGURE 2.7 A map of the lunar south pole (poleward of 87.5° S). Locations consistent with the presence of water ice based on anomalous ultraviolet reflectance, are indicated in cyan (Hayne et al. 2015). The grayscale indicates the maximum annual surface temperature; dark grays indicate regions of permanent shadow. Yellows asterisks mark the impact site of the LCROSS mission, and the planned landing region of VIPER. Data courtesy of Paul Hayne, and figure created by James Tuttle Keane.

The study of volatiles at the Moon continues into its exosphere. In the last ten years, a new appreciation of the exospheric hydrogen budget has been gained, where solar wind implanted protons can be backscattered as neutral hydrogen, energetic protons, or chemically altered in the regolith and released as new H-bearing species, including H_2 and methane. The LADEE mission did not find a substantial and sustained water exosphere. However, transient energetic water plumes were observed to be released from the surface during meteor streams, suggesting that the equatorial surface contains substantial amounts of H-bearing material either as water or OH that can be converted to water during highly energetic impactor events. LADEE also confirmed the presence of argon-40 and helium, found neon in comparable abundances, and discovered regional variations in the sodium and potassium exosphere. Further, a particulate exosphere, produced by micrometeoroid impacts, was found by LADEE to extend many hundreds of kilometers above the surface, though no evidence was found for electrostatic transport of dust at altitudes >1 km.

Over the past decade, numerous lunar space missions, analyses of lunar samples, and modeling approaches have deepened our understanding of the distribution of volatiles, impact history, magnetic field, and geological features not only for the Moon, but for early Earth and planetary objects in general. These observations have also raised new questions that will only be answered by returning to the Moon and making direct in situ measurements and by returning samples to study in laboratories on Earth.

Key Discoveries from the Past Decade

- **GRAIL explored the interior structure of the Moon with unprecedented detail, transforming our understanding of rocky worlds.** GRAIL produced the highest resolution gravity field measurements of any object (including Earth). This data revealed the Moon's crust to be far more fractured and porous than expected, exposed previously undiscovered global-scale magmatic-tectonic features, elucidated the formation and evolution of impact basins, and constrained models for both the bulk composition and formation of the Moon. While GRAIL focused on the Moon, these results have had sweeping implications for the understanding the geophysics of planetary bodies across the solar system.
- **New analyses of samples from the Moon provide key insights into its formation and physicochemical evolution.** Measurements of lunar samples have demonstrated the extent to which volatile elements are depleted in the lunar interior and the isotopic compositions of volatile elements, providing key insights into the process responsible for volatile depletion and at what stage(s) of the Moon's evolution the depletion occurred. Increasing evidence for the essentially identical isotopic compositions between Earth and Moon for non-volatile elements has strongly challenged prior Earth-Moon origin models. Additionally, paleomagnetic studies of lunar samples have revealed that the Moon once generated a core dynamo that persisted for over two billion years and had surface field strengths that, at times, rivaled that of the current Earth. Finally, geochronological studies of lunar samples have elucidated the Moon's formation age, which ties into our understanding of the timing of giant impacts during planetary accretion.
- **The Lunar Reconnaissance Orbiter (LRO) revealed the Moon in unprecedented detail, including ways in which its surface has been altered in recent geologic times.** Lunar volcanism was thought to have ended well over a billion years ago, but images from LRO revealed irregular patches of basaltic deposits that may have erupted within the past 100 million years. The locations of newly discovered tectonic features indicate the locations of tectonic features may be influenced by tidal interactions with Earth and from orbital recession away from Earth, and movement along these faults likely continues into the present day. Images of craters that have formed after LRO began its mission indicate that impacts affect the surface far from the impact site, and secondary cratering overturns regolith at rates over 100 times higher than previously thought.
- **Water ice lies at the surface within some regions of permanent shadow at the Moon's poles.** New results confirm that at least some polar H is present as H_2O, though its origin and abundance is still not known. Understanding the nature of the Moon's polar volatiles could provide insight into the origin, timing of delivery, and subsequent evolution of water and volatiles in the inner solar system.

Further Reading

Scientific Exploration of the Moon, Edited by J. W. Delano, *Elements*, v. 5, no. 1, pp. 11- 46, Mineralogical Society of America. ISSN 1811-5209.
New Views of the Moon 2, *Reviews in Mineralogy and Geochemistry*, v. 87, expected 2021, Mineralogical Society of America.
Lunar Exploration Analysis Group. 2019. Advancing Science of the Moon: Report of the Specific Action Team, held 7-8 August 2017, Houston, Texas, United States of America.

Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032

The Priority Science

6

Question 3: Origin of Earth and Inner Solar System Bodies

How and when did the terrestrial planets, their moons, and the asteroids accrete, and what processes determined their initial properties? To what extent were outer solar system materials incorporated?

Our inner solar system has the four terrestrial planets, Mercury, Venus, Earth, and Mars, along with Earth's large Moon, two small moons of Mars, dwarf planet Ceres, numerous 100-km class asteroids, and a multitude of small bodies that populate the asteroid belt and the inner planet region.[1] To what extent does this structure reflect a deterministic outcome of general solar system formation processes, and how much of it is instead a consequence of stochastic events that would change in unpredictable ways if the system's formation could be rerun? This fundamental question motivates scientific investigations of the inner solar system, with implications not only for understanding our own planet's origin but also for the origin of planetary systems and Earth-like planets beyond our own.

For example, general aspects of solid planet formation—including collisional accumulation from initially small planetesimals, temperatures too high for ice condensation in inner disk regions, and minimum orbital separations between large planets needed for stability—suggest that rocky planets close to their parent stars might be a common outcome of planet accretion. In contrast, processes such as giant planet migration and sporadic giant impacts may depend sensitively on conditions that vary greatly from system to system. The interplay between predictable and randomly determined events is an important theme in solar system origin. Study of our inner solar system worlds provides a uniquely valuable means to address this cross-cutting issue, thanks to their accessibility and the powerful constraints provided by the combination of remote observations and analyses of physical samples. Is our inner solar system—and our Earth—a typical outcome of planetary system formation, or is it an outlier compared to most systems in the universe?

Q3.1 HOW AND WHEN DID ASTEROIDS AND INNER SOLAR SYSTEM PROTOPLANETS FORM?

The classic model for the formation of asteroids and inner solar system protoplanets involves a transition from a proto-planetary gas nebula characterized by dust and gas to one populated by hundreds of 10^3 km sized bodies. Meteorites analyzed on Earth and asteroids studied in space preserve some of the compositional, mineralogical, and isotopic characteristics of these early formed bodies. The study of these remnants of solar system formation are a critical component for constraining both the physical and chemical characteristics of the terrestrial planets, as well as for understanding the processes that occurred in the protoplanetary gas nebula. However, many fundamental questions remain unanswered. We do not understand the origin of the materials these planetesimals derive from, or even if the current population of meteorites and asteroids is representative of the population that comprise inner solar system terrestrial bodies. Similarly, although we know that these small bodies undergo varying degrees of heating and

[1] A glossary of acronyms and technical terms can be found in Appendix F.

Questions : Question 3

This is a sample question from the Survey that might peak interest to you and your team. No need to go through this question if it does not apply to your science case. Additionally, notice that although this is Question 3, there are several subquestions! Here we include the entirety of Question 3.3.

Q3.3 HOW DID THE EARTH-MOON SYSTEM FORM?

Among our terrestrial planets, only Earth has a large satellite, and the Moon has affected our planet throughout its history. Lunar and terrestrial samples, together with spacecraft data, provide an extensive and powerful set of constraints on the origin of Earth-Moon, making this system unique in its ability to reveal conditions during the final stages of terrestrial planet accretion. The favored giant impact hypothesis proposes that the Moon formed as a result of a collision between the proto-Earth and another protoplanetary embryo, "Theia", at the end of Earth's main accretion (Hartmann and Davis 1975). The impact left Earth with its rapid early rotation rate, and produced a disk of iron-poor, highly heated debris, which later accreted into the Moon forming a primordial lunar magma ocean (LMO). Although this general model accounts for many characteristics of the Earth-Moon system, some characteristics have proved extremely challenging to explain, spurring development of a wide range of new impact models that are actively debated. Questions also remain regarding the timing of the giant impact.

Q3.3a What Are Physical Constraints on Earth-Moon System Origin?

Key constraints on how Earth and Moon formed include their compositional relationships, the Moon's age, and its initial thermal state. The extent of understanding of each of these constraints has evolved substantially in the past decade, yet many open questions remain.

Laboratory analyses continue to provide breakthroughs in understanding of how the compositions of lunar samples relate to those of terrestrial rocks. Much recent work focuses on isotopic compositions thought to best reflect the original feedstock of both bodies. Remarkably, the silicate Earth and Moon have nearly identical isotopic compositions for many elements (e.g., oxygen, titanium, chromium, silicon, tungsten), implying that they formed from a common source that was isotopically distinct from nearly all meteorite classes. The tungsten isotopic similarity is the most challenging to explain, requiring either a compositional match between the proto-Earth and Theia that is very improbable given their separate core formation histories, or complete mixing of protolunar material with Earth's mantle, potentially within vaporized phases produced during or after the impact. Better understanding of how late accretion (Q3.5d) affected Earth-Moon tungsten isotopic compositions, as well as how lunar and terrestrial rocks compare in highly refractory elements (e.g., Ca) less likely to vaporize, is important to further progress (Zhang et al. 2012). Disagreements remain as to whether Earth and Moon have identical oxygen isotopic compositions, or whether small differences between the two indicate that the Moon still partially records the composition of Theia (e.g., Young et al. 2016; Cano et al. 2020).

The Moon's volatile content may provide important constraints on the energetics of the giant impact and the conditions of the Moon's formation. Lunar samples are generally dry and depleted in volatile elements compared with terrestrial rocks, which are strongly volatile element depleted relative to most other planetary materials that have been analyzed. However, analyses of a small number of lunar samples, notably volcanic glass beads that trapped mantle melt, now show that at least portions of the early Moon were comparably water-rich to Earth's mantle (e.g., Hauri et al. 2015). The stable isotope composition of moderately volatile elements is slightly heavier and significantly more variable in lunar rocks than in terrestrial rocks (e.g., Wang and Jacobsen 2016). Accounting for these observations is challenging and has led to a variety of models of evaporative loss or partial condensation in the pre-lunar disk or by geologic processing on the early Moon (e.g., Canup et al. 2015; Day et al. 2017; Kato and Moynier 2017; Lock et al. 2018; Wang et al. 2019; Nie and Dauphas 2019).

An overall question is whether the Moon's composition is heterogeneous with depth, which would imply that lunar samples are not representative of the Moon's bulk composition. Improved constraints on the Moon's bulk composition, through additional samples originating in its deep interior (volcanic glasses or mantle exposed from the largest basin-forming impacts, particularly South Pole-Aitken basin) and/or a more thorough understanding of the Moon's geophysical structure, would be of great value.

Current estimates for the age of the Moon forming giant impact range from 4.52 to about 4.42 billion years ago, corresponding to about 50 to 150 million years after formation of the earliest solar system solids (e.g., Kruijer and Kleine 2017; Thiemens et al. 2019; Maurice et al. 2020). The large uncertainty stems from the fact that these estimates are based on assumption-laden models of isotopic evolution, which need to be assessed in the context of multiple geologically related events such as accretion, differentiation, and lunar magma ocean solidification (see Q3.6 and Question 5).

A fundamental issue for origin models is whether the Moon was completely or only partially molten when it formed—a so-called magma ocean. Multiple geophysical constraints seem to imply an initial solid lunar interior beneath the lunar magma ocean, including the history of tectonics and strain most recently revealed by GRAIL data (Andrews-Hanna et al. 2013), and a seismic transition that may represent the magma ocean base (Khan et al. 2006). However, alternative explanations exist that could permit a fully molten Moon given current data limitations and uncertainties. Resolving this issue is important because a partially molten Moon is difficult to reconcile with a giant impact origin, and thus would provide strong constraints on lunar origin models. Long temporal baseline geophysical and seismic data are needed to reveal the Moon's interior structure and to evaluate whether, e.g., it is consistent with layering expected for solidification of a magma ocean in a high thermal regime. Geochemical analyses of additional and more diverse crustal samples, as well as improved constraints on the Moon's bulk composition, would also contribute significantly to this fundamental issue.

Q3.3b What Was the Nature of a Moon-Forming Giant Impact(S) and Its Implications for the Initial States of Earth and Moon?

A canonical Moon-forming impact by a Mars-sized Theia can account for the masses of Earth and Moon, and the angular momentum of the system (e.g., Canup 2004). However, it produces a proto-lunar disk that originates primarily from Theia rather than from the proto-Earth. Meteorites that originate from Mars, and nearly all those from the asteroid belt, have substantially different isotopic compositions than Earth. If Theia were similarly non-Earth like, one would expect measurable differences between Earth and Moon. Instead, Earth and Moon are nearly isotopically indistinguishable for all non-volatile elements (e.g., Figure 6.1). A multitude of new concepts have been proposed to try to resolve this so-called "isotopic crisis" for the giant impact model. Notable examples include mixing and chemical equilibration of the silicate Earth with protolunar material before the Moon's assembly (Pahlevan and Stevenson 2007; Lock et al. 2018); high angular momentum/high energy impacts that produce "synestias" (Ćuk and Stewart 2012; Canup 2012; Lock et al. 2018); a "hit-and-run" impact (Reufer et al. 2012); formation of the Moon by multiple impacts (Rufu et al. 2017); and a Theia and proto-Earth that had similar isotopic compositions (Dauphas 2017).

The relative merit of these different models is a matter of active debate (e.g., Canup et al. 2021 and references therein), and progress will require improved understanding on multiple fronts. First, current thinking that Theia would have been isotopically distinct from Earth is heavily influenced by the isotopic composition of martian meteorites, the only other inner planet from which we have samples. Knowledge of the isotopic compositions of Venus and/or Mercury—currently unknown—is needed to address this fundamental issue and reveal the primordial feedstock of our innermost planets. Whether lunar materials could have thoroughly mixed with Earth's mantle prior to the Moon's assembly remains unclear, and needs to be assessed through modeling and observational tests. Explaining the Earth-Moon tungsten isotopic similarity (see above) remains challenging for all concepts save equilibration.

Another central issue is whether the Earth-Moon system angular momentum was greatly modified after the Moon formed. Tidal interaction between Earth and the Moon conserves their total angular momentum, but certain gravitational interactions involving the Sun could have slowed Earth's spin and reduced the system angular momentum by a factor of 2 or more soon after the Moon formed (e.g., Ćuk and Stewart 2012). If this occurred, it implies the Moon-forming giant impact was vastly more energetic than originally envisioned. Uncertainty persists because the spin-slowing mechanisms depend sensitively on the nature of