Planetary Science Priorities for the Moon in the Decade 2023-2032: Lunar Science is Planetary Science

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Big Questions in Planetary Science

This report focuses on key planetary science questions and how the Moon, an ideal laboratory for the study of planetary processes that occur across the Solar System, can provide answers. These big-picture questions were developed through an inclusive, community-driven process guided by the Executive Committee of the Lunar Exploration Analysis Group (LEAG), which worked over several months to develop a cohesive set of big-picture questions for planetary science using a process that included 1) a public call for inputs to the lunar exploration ("lunar-l") listserv maintained by LEAG Emeritus Chair Prof. Clive Neal of Notre Dame, which has over 900 subscribers; and 2) a Town Hall at the 2019 NASA Solar System Exploration Research Virtual Institute Forum at the NASA Ames Research Center.

Many members of the LEAG community have extensive trans-disciplinary experience and we worked to develop an inclusive set of questions relevant to the entire planetary science community. The Big Questions which arose from our community-driven process include:

1. *How do planetary systems form and evolve over time, and when did major events in our Solar System occur?*
2. *How do planetary interiors differentiate and evolve through time, and how are interior processes expressed through surface–atmosphere interactions?*
3. *What processes shape planetary surfaces, and how do these surfaces record Solar System history?*
4. *How do worlds become habitable, and how is habitability sustained over time?*
5. *Why are the climates of planetary bodies so diverse, and how did they evolve over time?*
6. *Is there life elsewhere in the solar system?*

Of these six questions, scientific study of the Moon can play a pivotal role in addressing the first four. The last in-person meeting of LEAG, October 28–30, 2019 in Washington D.C., held sessions devoted to examining how lunar science can contribute to these four questions. This report is a summary of the LEAG community consensus of the high-priority topics in lunar science that must be addressed in order to gain new insight into fundamental planetary science questions. These priorities are informed by several guiding documents including the 2007 National Research Council report, *The Scientific Context for Exploration of the Moon* (referred to as the SCEM report), the 2017 LEAG Specific Action Team Report *Advancing Science of the Moon* (ASM-SAT), and the LEAG-maintained *United States Lunar Exploration Roadmap*.

1. How do planetary systems form and evolve over time, and when did major events in our Solar System occur?

Many aspects of the origin and evolution of planetary systems remain unconstrained, including their dynamics, bombardment chronology, and characteristics of nascent planetary systems. We can use our Solar System as a benchmark for understanding others, and we can use the Moon as a key location to better understand many aspects of planetary system evolution.

For example, the origin of the Earth–Moon system created extreme temperatures and pressures similar to those occurring during planetary accretion. These extreme conditions are recorded within the lunar rock record and therefore can be used to address many high-priority scientific questions, including: When did the collision between the impactor and the proto-Earth occur? What were the mechanisms, timing, and extent of volatile depletion in the Moon? What is the nature of isotopic similarities and differences between the Earth and Moon, and how can they constrain the composition of the Mars-sized impactor? What were the physicochemical conditions and processes that operated in the protolunar disk? What were the physicochemical conditions and processes that operated at the surface of the lunar magma ocean? Was there an early lunar atmosphere, and what was its composition and longevity?

The Moon provides a crucial record of the bombardment history of the inner Solar System. Identifying and characterizing evidence of the Late Heavy Bombardment on the Moon would provide a unique perspective on a Solar-System-wide event that affected all the rocky planets of the inner Solar System. In addition, determining the size–frequency distribution of impact craters on a surface remains one of the only methods for estimating ages of features on many planetary bodies, and the Moon's crater record is the benchmark for analyses of craters on other planetary bodies. **As such, establishing an accurate bombardment chronology on the Moon is of the highest importance for future analyses on all rocky planetary bodies in our Solar System.** Many foundational science questions that are relevant for establishing the bombardment history of the inner Solar System could be addressed at the Moon: What are the formation ages of key lunar basins (e.g., Orientale, Crisium, Nectaris, Schrodinger, South Pole–Aitken), and what form of the Late Heavy Bombardment do they support (i.e., cataclysm, sawtooth, monotonic decline)? What is the recent impact flux? How do secondary impacts affect crater counts?

Several topics relating to bombardment were discussed in the previous decadal survey and are still relevant science questions, including: What causes changes in the fluxes and intensities of meteoroid impacts on terrestrial planetary bodies, and how do these changes affect the origin and evolution of life? How can we use the impact record of the Moon to understand the environmental effects of large impacts on terrestrial planets?

Other relevant white papers on these topics include: bombardment across the Solar System: early years (W. Bottke), recent years (B. Ghent, N. Zellner); sample return from South Pole Aitken Basin (B. Jolliff); sample return from young Mare basalts (S. Lawrence), improving Solar System chronology (S. Robbins, C. Fassett, M. Kirchoff); and framework for absolute ages across the inner Solar System (B. Cohen).

2. How do planetary interiors differentiate and evolve through time, and how are interior processes expressed through surface-atmosphere interactions?

The interiors of planets can be assessed through various methods including performing geophysical studies, assessing volcanic processes, and identifying the nature of planetary outgassing. Better understanding the nature of the lunar interior, including processes of differentiation and evolution over time, the formation and evolution of the lunar magma ocean, and subsequent geologic processes manifested at the surface, will also help us to characterize and better understand other planetary interiors.

Characterizing the current lunar interior structure (via methods such as remote sensing, in situ studies, and/or analyses in terrestrial laboratories) would enable investigations of early differentiation and evolutionary processes. These investigations could address questions such as: what is the extent, duration, fate, and consequence of a planetary magma ocean? Was there a large-scale overturn of the lunar mantle and when did it occur? What is the state of the lunar core? What is the history of the lunar dynamo and how was it sustained? How does the present-day evolution of the lunar surface reflect interactions of the Earth-Moon system through time?

The origin and formation of the Moon’s nearside/farside asymmetry remain a mystery, and motivates investigations into the nature of planetary asymmetries and how they reflect early evolutionary processes. By studying the specific nature of the lunar asymmetry, through analyses such as the tectonomagmatic evolution of the Procellarum-KREEP Terrane, it may be possible to address the origin of asymmetries on other planetary bodies.

The nature of planetary interiors is perhaps most easily analyzed by studying the products of volcanism. The thermal and compositional properties of a planet’s interior will directly affect the distribution, age, thickness, and morphology of volcanic products. By studying lunar volcanic materials, we can also better understand the Moon’s initial bulk composition and further constrain the composition of the bulk crust and mantle. By studying the secondary planetary crust formation processes on the Moon, many questions can be addressed including: How do the chemical and mineralogical properties of volcanic products reflect the differentiation history, structure, and convective mixing of the lunar interior? How do the distribution, types, and ages of lunar volcanic deposits reflect the variability of the lunar interior?

Other relevant white papers on these topics include: the Moon is a special place (D. Moriarty, C. Neal, S. Lawrence); recent outgassing on the Moon (D. Needham); primary and secondary crust formation and preservation on the Moon (J. Head, L. Kerber); special instances of bedrock exposures on the Moon (L. Kerber); geophysical science campaign for the Moon (R. Weber, C. Neal); high priority returned lunar samples (S. Valencia); and origin and evolution of the Procellarum KREEP Terrane (B. Jolliff).

3. What processes shape planetary surfaces and how do these surfaces record Solar System history?

The surface of the Moon is a record of over four billion years of geologic processes. Studying the various geologic features present on the Moon is necessary to better understand the types of processes that affect all planetary objects, but especially airless rocky bodies. Volcanism, impacts, and regolith development occur on many planetary bodies, but certain features may have formed due to specific conditions on the Moon, such as magnetic anomalies. Each of these features and processes can address fundamental Solar System science.

3.1 Magnetic Anomalies

Magnetic anomalies remain enigmatic features that enable studies of lunar magnetism and interactions of the solar wind with the surface. By studying the origins of magnetic anomalies we can determine if local magnetic fields formed from a core dynamo or from cometary impacts. Additionally, analyses of these features could determine whether there are materials present in the subsurface that retain magnetic properties. By studying how the solar wind interacts with the lunar surface, questions can be addressed that are relevant for other airless bodies such as Vesta, Ceres, and Mercury: To what extent does the solar wind contribute to overall space weathering compared to micrometeoroid impacts? What are the mechanisms of dust charging and transport and what role does micrometeoroid impact vaporization play in the generation of an exosphere? How spatially variable are solar wind effects? What are the physical interactions of hydrogen with mineral surfaces, and how is hydrogen formed and retained in surface minerals?

3.2 Polar Volatile Deposits

The polar regions of the Moon and Mercury contain microenvironments of permanent shadow that are unique in the Solar System. Deposits of trapped volatiles have been identified in these permanently shaded regions which represent valuable science targets, but many questions remain about the origin, formation, and characteristics of the volatiles. Several high-priority science questions could be addressed by further investigating polar volatile deposits: How much ice (and other volatiles such as CO_2 and organic-rich compounds) is in the permanently shadowed regions of the Moon? What are the forms, concentrations, and spatial distributions of volatiles? What are the ages and isotopic signatures of volatiles? What is the nature of the lunar water cycle and how is it related to polar volatiles? Is there spatial/temporal variability to polar volatile deposits? What process(es) controls volatile transport, modification, and deposition?

3.3 Regolith

The formation and evolution of regolith is a complex process that includes physical and chemical interactions on an airless body with impactors and the solar wind. The Moon is an easily accessible laboratory in which to study how regolith forms and evolves, which will yield insights into similar processes on other airless bodies such as Mercury and asteroids. Regolith analyses would enable us to further determine what controls space weathering and the products of solar wind versus micrometeorite bombardment, as well as identify the source of variability in regolith development on airless bodies (e.g., variations on Phobos/Deimos and the Moon).

3.4 Impact Craters

Impact cratering is the most ubiquitous geologic process across all planetary bodies, regardless of size or location in the Solar System. The formation of impact craters is exceedingly complex, and many questions still remain about the specific mechanisms that operate during an impact event: How does impact melt form and differentiate? What is the specific mechanism by which uplift occurs in central peaks and peak rings? How does ballistic sedimentation occur? What is the fine-scale process of shock metamorphism? How does impact gardening lead to regolith evolution and maturation on a microscale? What are the seismic implications of impacts? What are the ages of the oldest and youngest lunar basins?

3.5 Volcanic Features

Volcanism is a foundational planetary process that is diagnostic of a planet's thermal and compositional characteristics and evolution. Lunar volcanic features illustrate how secondary crust forms on a one-plate planetary body, and characterizing the diversity of lunar volcanic eruptions, constructs, and end-members will be informative for analyses of volcanism throughout the Solar System. Studies of lunar volcanism can address many high-priority scientific questions: Does intermediate-style volcanism exist on the Moon? How much basaltic versus silicic material exists on the Moon, and when was it erupted? What is the age of the oldest and youngest volcanic activity on the Moon, and what are their compositions and volumes? How has the volcanic flux changed through time?

Other relevant white papers on these topics include: Next Generation Lunar Orbiter (T. Glotch); mobility and contextualizing samples for sample return (K. Young); recent impacts and effect on the surface (E. Speyerer); space weathering across the Solar System (M. Thompson); options for rover or static lander missions at a magnetic anomaly (D. Blewett); the plethora of science afforded by a lunar swirl (G. Kramer); dust charging and transport, and effects on surface evolution (X. Wang); volcanism on the Aristarchus plateau (E. Jawin); silicic volcanism on the Moon (S. Valencia and R. Watkins); and volcanism across the Solar System (L. Kerber).

4. How do worlds become habitable, and how is habitability sustained over time?

While the Moon does not currently contain environments conducive to the formation and evolution of life, it likely influenced the formation and evolution of life on Earth. Therefore, topics related to habitability can be addressed by studying the Moon, including its impact history (as noted above) and the formation, transport, and delivery of volatiles. The volatile history of the Earth–Moon system may also be preserved on the Moon.

The lunar magma ocean formed during the earliest part of the Moon's history, and induced extreme, potentially unique, conditions in the history of the Moon. Studies devoted to understanding the lunar magma ocean would help to constrain the endogenous volatile content and thermal evolution of the early Earth-Moon system, and could determine outgassing rates on the Moon that may have created an early atmosphere.

The polar cold traps on the Moon contain deposits of water ice. Additionally, recent indications of dark, potentially organic, volatiles near Mercury's poles suggest that similar materials may also be present at lunar polar cold traps. Understanding the formation and evolution of these cold traps, and the method by which organic materials may have accumulated, would allow us to characterize the volatile record on the Moon, both through exogenous processes such as impact and solar wind implantation, and endogenous sources such as volcanism. Additionally, studying the compounds present in polar deposits could allow for analyses of prebiotic chemistry in cold environments that could inform our understanding of primitive bodies that exist elsewhere in the Solar System.

The emergence and development of life on Earth can also be addressed by studies of the Moon. Impacts onto the early Earth may have caused localized or global extinction events, but the records of ancient impacts on Earth have mostly been erased due to plate tectonics and other terrestrial processes. As a one-plate body, the Moon can act as a witness plate for the impact flux onto the early Earth, which can help to constrain conditions that influenced the emergence of life. Identifying terrestrial meteorites on the Moon or in lunar samples could also provide context for the history of terrestrial impact bombardment. In addition, the Moon may contain a record of the evolution of the Sun and the ancient radiation environment present in the Earth/Moon system. Variations in the cosmic and solar fluxes may have affected the emergence of life on Earth, evidence of which could be preserved in the lunar geologic record.

Relevant white papers on these topics include: Polar Ice Prospecting Explorer for Lunar No-light Environments (PIPELiNE) (D. Hurley); the water cycle network (P. Clark); lunar polar volatile resources: obtaining their origins prior to extraction (W. Farrell); and lunar volatiles and Solar System science (P. Prem).

Recommendations

Several guiding documents put forward by the lunar community present prioritized recommendations for future lunar science that are still valid, including the SCEM report, ASM-SAT, and the Lunar Exploration Roadmap. We echo the suggestions from those documents and refer the reader to the original reports.

We also recommend that the Decadal Survey **consider the critical role of team dynamics, equity, diversity, inclusion, and accessibility in planetary science.** In order to address the four big questions in planetary science outlined in this report, a multitude of perspectives and expertise areas must be integrated. Studies of scientific teams have found that team members with diverse expertise areas develop resources and synergies that result in an end product that adds up to more than the sum of its parts (Balakrishan et al., 2011). In addition, sociological studies have demonstrated that groups are more innovative (Burt, 2004; Powell et al., 1996; de Vaan et al. 2015) and have higher-impact outcomes (de Vaan et al., 2015; Curral et al., 2001) when they foster strong connections across sub-units.

It is also critically important that the planetary science community fosters an environment that is interdisciplinary, diverse, equitable, inclusive, and accessible to everyone. We strongly encourage the Decadal Survey to consider issues of equity, diversity, inclusion, and accessibility—not as distinct issues, but as necessary steps on the pathway to addressing fundamental questions about planetary science. Supporting information regarding the current lack of diversity in the planetary science community and specific, actionable, and practical recommendations can be found in white papers including: Who is missing in planetary science?

Demographics showing Black and Latinx scientists are the most underrepresented (E. Rivera-Valentín); recommendations to increase the number of Black and Latinx scientists (J. Rathbun); non-binary inclusion in planetary science (B. Strauss); why is diversity important? (M. Milazzo).

Big Question	Relevance (Link to SCEM/ASM-SAT Goals)
1. How do planetary systems form and evolve over time, and when did major events in our Solar System occur?	SCEM goal 1 ASM-SAT goal The Origin of the Moon
2. How do planetary interiors differentiate and evolve through time, and how are interior processes expressed through surface-atmosphere interactions?	SCEM goals 2, 3, 5, 8 ASM-SAT goal The Origin of the Moon ASM-SAT goal Lunar Tectonism and Seismicity ASM-SAT goal The Lunar Water Cycle
3. What processes shape planetary surfaces and how do these surfaces record Solar System history?	SCEM goals 1, 4, 5, 6, 7, 8 ASM-SAT goal The Lunar Water Cycle
4. How do worlds become habitable, and how is habitability sustained over time?	SCEM goals 1, 4, 5, 6, 7, 8 ASM-SAT goal The Lunar Water Cycle ASM-SAT goal The Origin of the Moon

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