LUNAR MISSIONS FOR THE DECADE 2023-2033

A White Paper to the 2023 Planetary Science Decadal Survey

Authors:
Barbara Cohen* (NASA Goddard Space Flight Center), LEAG Vice-Chair
Sam Lawrence (NASA Johnson Space Flight Center), LEAG Chair
Brett Denevi (JHU Applied Physics Laboratory), LEAG Vice-Chair
Timothy Glotch (Stony Brook University)
Dana Hurley (JHU Applied Physics Laboratory)
Clive R. Neal (University of Notre Dame)
Mark Robinson (Arizona State University)
Ryan Watkins (Planetary Science Institute)
Renee Weber (NASA Marshall Space Flight Center)

*Barbara.A.Cohen@nasa.gov | (256) 975-1274

1. Introduction

Lunar science presently has a well-developed slate of key science questions that are profoundly impactful for understanding the formation and evolution of the Solar System: How do terrestrial planetary bodies differentiate and lose heat over time? Was there a late heavy bombardment throughout the Solar System and when did it end? What is the origin and life cycle of volatile deposits on airless bodies? Consensus lunar science priorities have been described and reaffirmed in community documents: The Scientific Context for Exploration of the Moon (SCEM; National Research Council, 2007), Advancing Science of the Moon Specific Action Team report (ASM-SAT; LEAG 2018a), and the Lunar Exploration Roadmap (e.g., Fagan, 2020). Multiple lunar missions in the next Decade would be able to address the questions elucidated in those planning documents, missions that would result in dramatic, paradigm-shifting advances that would extend well beyond the Moon. In the course of preparing for the 2023 Decadal Survey, the Lunar Exploration Analysis Group (LEAG) held several activities to gain community input on the science that should be accomplished in the next decade across a range of mission classes (New Frontiers, Discovery, SIMPLEX, etc.). In this White Paper, we summarize these community-driven endorsements and make the following recommendations to the Decadal Survey:

- Include a Lunar Geophysical Network as a New Frontiers mission if it is not selected in New Frontiers 5.
- Include a Solar System Chronology mission in New Frontiers to be accomplished by sample return or *in situ* dating.
- Initiate a study within the Decadal Survey for a Lunar Permanently-Shadowed Region Volatiles Explorer mission to a large PSR (e.g., Shackleton, Cabeus, Craters)
- Initiate a study within the Decadal Survey for a Next Generation Lunar Orbiter mission
- Add a Long-Range Geologic Explorer to the New Frontiers list.
- Advocate for lunar missions that accomplish Solar System science in the Discovery and SIMPLEX programs.

- Investigate potential mission partnerships with other Science Directorates to leverage the unique opportunities of the Moon as a science platform
- Highlight enabling technology investments via PSD technology programs and in partnership with the STMD Lunar Surface Innovation Initiative.

2. New Frontiers Missions

We have not set relative priorities on the four NF missions LEAG advocates because each contributes to a different facet of Solar System science, and as such, should be considered within the scientific goals set by the Decadal Survey panels. LEAG strongly supports using the decadal survey process to identify specific science priorities that should be addressed within the New Frontiers program. This process is the best route for building community consensus for large, high-priority, PI-led missions. Any changes to the New Frontiers target list should be made via a formal, community-focused process, as recommended in the Planetary Decadal Midterm Review.

2.1 Lunar Geophysical Network (LGN)

The Lunar Geophysical Network (LGN) mission will reveal the initial stages of terrestrial planet evolution. Terrestrial planetary bodies all share a common structural framework (crust, mantle, core) that is developed very shortly after formation, and which determines subsequent evolution. While much of Earth's early structural evidence has been destroyed by plate tectonics, the heat engine that drove differentiation of the Moon waned after the first ~2 b.y. of lunar history as the volume of magmatism decreased dramatically, meaning that some evidence of early differentiation events is likely preserved, as indicated by modeling of mare basalt source regions. The structure and composition of the lunar interior therefore provides fundamental information on the initial evolution of any differentiated terrestrial planetary body (Weber et al. 2020).

Geophysical instruments deployed on the Moon during Apollo revolutionized our understanding of the lunar interior. But there are fundamental issues remaining regarding the detailed global structure of the Moon's deep interior, which has bearing on its thermal, petrological, and rotational history: 1) The mineralogy and temperature of the upper mantle, nature of the lower mantle, the size, state, and composition of a lunar core, and the composition and structure of an inner core remain to be unequivocally established. 2) The structure, composition, and heterogeneity of the deep lunar interior below ~1,000 km is not constrained, nor is whether and how surface terrane dichotomies extend into the interior. 3) Only eight out of over 300 known deep moonquake source regions are likely located on the lunar farside. Are there other source regions on the farside that were not detected by the Apollo nearside array? What is the nature and extent of the purported plastic (attenuating) zone and what implications does this have for lower mantle structure? What is the mechanism for triggering deep moonquakes? 4) The exact origins of shallow moonquakes are unknown. While Lunar Reconnaissance Orbiter (LRO) data suggest they are associated with thrust faults, this remains a hypothesis that needs to be tested. 5) Apollo heat flow measurements were at sites close to the boundary between the Procellarum KREEP Terrane and the Feldspathic Highlands Terrane, so true lunar heat flow remains a modeled quantity rather than constrained by definitive data. 6) The electrical conductivity structure of the outermost 500 km of the Moon and its lateral variations remains unconstrained.

In the past decade, the NASA Gravity Recovery and Interior Laboratory (GRAIL) mission mapped the gravity of the Moon at the highest resolution for any Solar System body. GRAIL data revealed features of the lunar crust in unprecedented detail and produced a family of core models consistent with geodetic parameters and seismic constraints. However, the global GRAIL data are constrained by the Apollo seismic data and carry its associated uncertainties. A globally distributed, long-lived LGN would deliver data to address the questions above and add greater fidelity to GRAIL data. Each LGN station could be instrumented to measure seismic activity, magnetic and electrical fields, heat flow, and retroreflectors for laser ranging from Earth (Neal et al. 2020). Establishing a network of long-lived, globally distributed geophysical stations on the Moon would permit us to address fundamental questions in Solar System science. **Our community advocates including a Lunar Geophysical Network as a New Frontiers mission if it is not selected in New Frontiers 5.**

2.2 Solar System Chronology

Establishing an absolute lunar impact chronology has important ramifications for understanding the early structure of the Solar System, and the evolution of both the of the dynamics and composition of the bodies. The ages of planetary surfaces throughout the Solar System are based on the observed density of impact craters calibrated using radiometric ages of Apollo and Luna samples. Unfortunately, the lunar cratering record itself is unconstrained prior to the apparent bombardment of 3.9 Ga, and suffers from a roughly billion-year uncertainty between 1 and 3 Ga. Therefore, refining the lunar crater chronology curve and using it to calibrate body-specific chronologies is critically important for comparing planetary histories, contextualizing Solar System dynamics, and developing an interplanetary perspective on the evolution of planetary surfaces, interiors, and habitable environments (Bottke, 2020; Cohen et al. 2020a).

The leading, but contentious, model for lunar impact history includes a pronounced increase in large impact events between 4.1 and 3.9 Ga. This cataclysm would also have bombarded an Earth and Mars that had atmospheres, oceans, and continents, and may have influenced the course of biologic evolution. The dynamical models to explain such a phenomenon rearrange the architecture of our Solar System and are invoked to explain the arrangement of exoplanets around other stars. A key test of this scenario is whether the terrestrial planets and asteroid belt experienced a relative "lull" in impacts between accretion and late bombardment, using detailed geochronology of samples from lunar basins. As the oldest stratigraphically recognizable basin on the Moon, an absolute age for the South Pole-Aitken Basin (SPA) would anchor the flux curve very early in planetary history (Jolliff et al. 2020). Recent remote sensing work has also identified impact-melt exposures in the nearside Nectaris and Crisium basins, benchmark pre-Imbrian basins whose ages would also provide strong constraints on the onset and duration of a cataclysm (Cohen et al. 2020b). Our community reaffirms the high priority placed on resolving lunar basin chronology, which would provide insight into Solar-System-wide bombardment, the conditions under which life emerged on Earth, and the differentiation and evolution of the lunar interior.

Expanding the absolute chronology of the post-basin era will require measuring radiometric ages of samples with well-established provenance, including young mare basalts and key stratigraphic craters. Under the "classic," sample-based lunar chronology, mare volcanism is thought to have reached its maximum volumetric output between 3.8 and 3.2 Ga. New crater-density relationships imply that peak volcanism may have extended for an additional 1.1 Ga, a finding that would dramatically revise our understanding of the thermal evolution of the lunar mantle, the abundance and distribution of radioactive heat-producing elements and the release of indigenous lunar volatiles.

Absolute age measurements of young lunar basalts and irregular mare patches would both refine our understanding of the duration of lunar volcanism and propagate forward to improved chronologies for other planetary bodies.

The importance of constraining the lunar impact history has been reaffirmed in the last two Planetary Science Decadal Surveys; however, the recommended mission (SPA sample return) reflects the reality that for those decades, sample return was regarded as the only way to provide reliable and interpretable geochronological constraints on planetary bodies. However, NASA investments have brought the instruments that can measure ages using complementary radiogenic isotopic systems (K-Ar and Rb-Sr) to TRL 6 by the time of the next Decadal Survey. Feasible New Frontiers-class missions could carry a capable instrument payload to conduct *in situ* dating with the precision to answer community-identified science goals, including cataclysmic bombardment and planetary volcanism (Cohen et al. 2020b). Additionally, new remote sensing, geologic mapping, and site evaluation efforts have expanded the locations where safe landing sites can access datable lithologies to answer these questions. The implementation architecture for understanding Solar System chronology in *Visions and Voyages* is unduly prescriptive, allowing only SPA sample return. Allowing proposals for missions that address the science goals of improving Solar System chronology by SPA sample return, sample return from other locations, or *in situ* dating, could take advantage of both recent advances in science and creative implementation solutions emerging from the planetary science community. **We advocate that this Decadal Survey include a New Frontiers mission that encompasses the chronology of the inner Solar System, setting the science goals but allowing flexibility in implementation.**

2.3 Lunar Polar Volatiles Explorer

Orbital and impact missions over the past two decades have provided a wealth of new data concerning the nature of volatiles in the lunar polar region. Measurements from orbit demonstrated that volatiles in lunar polar regions are heterogeneously distributed, likely with the patchiness continuing on scales smaller than observation spatial scales (100 meters to 30 kilometers). Interest in the special environment of the lunar poles has grown dramatically, but an understanding of polar volatiles and the fundamental questions about their origin and evolution remain unanswered (Prem et al. 2020). Lunar polar volatiles are thought to contain evidence of the historical flux of comets to the inner Solar System, records of changing thermal environments through a theorized epoch of polar wander on the Moon, and even gasses released from the interior during periods of volcanism. However, these volatiles have been modified over time by exposure to UV light from interplanetary hydrogen atoms, sputtering by ions and electrons from the solar wind and Earth's magnetosphere, bombardment by meteoroids large and small, radiolysis from cosmic rays and other energetic particles, long-term obliquity variations, and thermal effects. While this dynamic environment complicates relating the present abundance of volatiles to their original amounts and source(s), it provides a means to study fundamental processes acting on airless bodies throughout the Solar System, and in exoplanetary systems (Lucey et al. 2020).

Very little progress has been made on polar volatile goals of the SCEM and ASM-SAT report because determining the species and their abundance requires in situ measurements from Permanently Shaded Regions (PSRs). In situ studies of PSRs will reveal: 1) the distribution of volatiles laterally and with depth; 2) the effects of fundamental processes modulating the distribution of volatiles, and 3) the environmental factors such as temperature, ion flux, impact history, and regolith composition. Directly measuring the present-day transport, alteration, and loss processes that operate on volatile materials at PSRs will revolutionize our understanding of these effects. Quantifying and mapping the composition of deposits within the PSRs and characterizing their environments are also an operational tool for in situ resource utilization (ISRU). The scientific goals of studying lunar volatiles are synergistic with the observations required to close strategic knowledge gaps that enable ISRU (LEAG VSAT, 2016).

The VIPER mission, scheduled to launch in 2023, is a critical first step at providing ground truth for our understanding of polar volatiles. It will characterize volatiles at a site of interest for human exploration. However, it will not delve deeply into the coldest, oldest PSRs where we expect to find the most complete record of volatile composition and contributions from the oldest sources. In the next decade, a landed/mobile mission definitively identifying the composition, abundance, and distribution of volatiles in an extremely cold lunar PSR should be a high priority (Hurley et al. 2020). A New-Frontiers class Lunar Polar Volatiles rover mission was considered in Visions and Voyages, but its implementation was considered immature relative to the state of the science. That situation is now inverted, with the lack of in situ ground-truthing data now limiting our scientific understanding of lunar volatiles. A lunar polar volatile mission was therefore included in the priority study areas recommended by the Committee on Astrobiology and Planetary Science (CAPS, 2017) but a corresponding Planetary Mission Concept Study (PMCS) study was not selected. **We recommend the Decadal Survey initiate a Lunar PSR Volatiles Explorer mission study and consider it for inclusion in the New Frontiers mission list.**

2.4 Long-Range Geologic Explorer

Although there exists a simple paradigm for the lunar crust (a primary crust of anorthositic highlands modified in places by basaltic lavas that flowed across the surface early in lunar history), fragments of Apollo samples and lunar meteorites, and remote sensing observations from LRO, Kaguya, Chang'E 1 and 2, and GRAIL, suggest the nature and evolution of lunar magmatic and volcanic activity was far from simple. Vertical and lateral variations in composition, style of emplacement, and age reveal the evolution of a terrestrial body, preserved in unique locations across the lunar surface as records of distinct outcomes of varied experiments run to completion. Nowhere on the Moon is this diversity of crustal materials and styles of magmatism as apparent as in Oceanus Procellarum.

An investigation of northern Oceanus Procellarum with a capable rover would enable a traverse through four billion years of lunar magmatic history, addressing three key scientific themes: 1) Evolution of the lunar interior and nature of Procellarum KREEP Terrane (PKT), 2) Diversity of styles of magmatism, and 3) Post-emplacement modification of magmatic materials, including space weathering, cratering, and regolith development. Straightforward measurements (elemental, spectral reflectance, imaging, space environment, magnetic) will provide a scientific return that will redefine our understanding of fundamental planetary processes (including crustal formation, volcanology, impact cratering, and regolith processes) while making existing (and future) orbital remote sensing measurements more valuable.

The Intrepid mission concept (Robinson et al., 2020) studied the feasibility of a long-range lunar geologic rover, relying on high TRL hardware, advanced autonomy, detailed traverse pre-planning, night operations, and a disciplined concept of operations enabling an investigation of over 130 major and 900 minor scientific sites along an ~1800 km traverse over the course of four Earth years. Intrepid would touch down just south of the Reiner Gamma magnetic anomaly and traverse across and along the "swirl" to definitively test origin hypotheses for the anomaly and swirl (dike >4 Gyr, basalts 3.3 to 3.5 Gyr). It would then continue to the Marius Hills volcanic complex to investigate cones, flows, vents, and putative volcanic ash deposits (2.5 Gyr to 3.3 Gyr), and head north across some of the youngest (1.2 Gyr to 1.9 Gyr) lunar mare deposits, making a suite of compositional observations of the mare and spectacular rays from Aristarchus crater to test hypotheses concerning the existence of KREEPy basalts and ray mixing systematics. Once on the Aristarchus plateau, Intrepid would characterize the largest pyroclastic deposit on the Moon (perhaps 2.5 Gyr), unlocking the deep mantle and enable prospecting for H deposits, and then traverse the southern and eastern rim of the impressive Aristarchus crater (0.1 to 0.2 Gyr), assessing ejected material from deep within the PKT (3.5 Gyr to >4.0 Gyr). Finally, Intrepid would investigate a newly discovered type of volcanic landform, Irregular Mare Patches (IMP), which are proposed to represent very young (<100 Myr) volcanism. **We advocate that the Decadal Survey add a Lunar Long-Range Geologic Explorer to the New Frontiers list.**

2.5. Next Generation Lunar Orbiter

The Lunar Reconnaissance Orbiter (LRO) has provided paradigm-shifting insights into the lunar volatile cycle, volcanism, crustal evolution, regolith processing, and impact and tectonic histories over its primary and extended missions and has also contributed to the retirement of several lunar SKGs, demonstrating that long-lived orbital missions are crucial for the success of future landed robotic and human missions. After more than a decade in lunar orbit, LRO is an aging asset that is unlikely to remain functional until the next Decadal Survey process. After LRO completes its mission, there will remain a need for a large long-lived orbital platform carrying co-aligned instruments that can make simultaneous measurements across multiple wavelengths and spatial scales. An advanced large orbiter would extend our understanding the origin and diversity of the Moon and terrestrial planets by contributing to the understanding of the geochemistry and geology of the Moon at previously unattainable spatial and spectral resolutions among lunar mission data. This orbiter would enable instruments with mass or power requirements that are too high for existing cubesat and smallsat configurations to advance consensus lunar scientific priorities and support landed missions over the next decade (Glotch et al., 2020). The orbiter would also enable long-term landing site scientific and hazard characterization, communications relay for landed assets, and, potentially, quick response high resolution imaging of human activity on the lunar surface. **We recommend the Decadal survey initiate a Next Generation Lunar Orbiter mission study and consider it for inclusion in the New Frontiers mission list.**

3. Discovery, SIMPLEX, and other missions

At the LEAG Annual Meetings in 2018 and 2019, more than 30 cubesat, smallsat, Discovery, and New Frontiers concepts with compelling Planetary Decadal level science objectives, were presented in the "Preparing for the next Decadal Surveys" community forum. The LEAG ASM-SAT report highlighted that there are new science measurements that can be made with both landed and orbital assets. LEAG is committed to fostering discussion and refinement of science goals and bringing scientists and engineers together to reach innovative architecture solutions for the PSD portfolio. **We strongly recommend that lunar science goals stand on equal footing with other Solar System science goals in these competitive, PI-led programs.**

4. Partnerships with other Science Directorates

LEAG also strongly supports concepts for heliophysics and astronomical observations from the Moon, some of which are being considered in the ongoing Astro2020 Decadal Survey. Several compelling mission concepts were discussed in the LEAG 2018 "Preparing for the Next Decadal Surveys" community forum. **We recommend that the Decadal Survey urge NASA to investigate potential partnerships with other Science Directorates that would leverage the unique opportunities of the Moon as a platform.**

5. Relationship to other NASA Agency activities

LEAG enthusiastically commends the myriad of opportunities for science enabled by the other Agency activities in the Moon-to-Mars initiative, including the VIPER mission and the Commercial Lunar Payload Services (CLPS) program. The LEAG community recognizes the CPLS program as a way to increase competition, drive down costs, provide flight opportunities for multiple payloads, increase the diversity of our field, and define a bold new paradigm of conducting planetary science research in this country. Multiple use cases have been studied (LEAG, 2018b) and the Intrepid PMCS mission concept would take advantage of a CLPS-provided lander for lunar delivery.

However, we strongly affirm that these activities, as currently formulated, are not replacements for, or alternatives to, Discovery and New Frontiers-class lunar missions. The LEAG executive committee was surprised to see the 2020 Discovery Selection Document state that "…NASA is already making significant investments in lunar exploration and investigation, making NanoSWARM a lower priority than the selected investigations for the programmatic reason of maintaining scientific balance." It is utterly dismaying that a Category 1 Discovery mission would be prioritized lower than other missions on the basis of NASA investments that have yet to demonstrate they can return science results on the level expected of a Discovery (or New Frontiers) mission.

CLPS is a relevant example of the rise of commercial entities, public/private partnerships, and philanthropic spaceflight NASA and the nation are considering as new modes of acquisition and new opportunities for implementation. Once the Decadal Survey provides science priorities, NASA should be given leeway to implement them using all the tools at their disposal, including R&A, competed and directed SMD missions, HEO partnerships, pay-for-data or pay-for-delivery commercial models, public/private partnerships, and philanthropic spaceflight. Other science areas, such as Planetary Defense and Mars exploration, also stand to benefit from these diversified modes of acquisition. However, we emphasize that there are compelling science activities at the Moon that require resources commensurate with Discovery and New Frontiers calls. These should be considered on their merits and on even footing with respect to missions to other destinations. **We recommend that the Decadal Survey emphasize that lunar missions accomplishing Solar System science goals should be included in the PSD portfolio.**

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