Why the Moon is important for Solar System Science

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The Moon is our closest celestial neighbor and represents a nearly complete picture of the processes that have influenced the inner solar system over time, especially the period >3 b.y. ago, which has been obscured/lost on Earth. The Moon also represents the only other planetary body that humans have visited. Investigations carried out on the lunar surface, coupled with returned samples and lunar meteorites, and data from orbital missions, have allowed sophisticated scientific questions to be posed regarding the formation and evolution of the Moon and the inner Solar System. ***Many of the discoveries from our studies of the Moon have become the paradigms for the evolution of the terrestrial planets.*** Three fundamental scientific concepts emerged: (1) lunar origin by giant impact, (2) the existence of an early lunar magma ocean, and (3) the potential of an impact cataclysm at 3.9 billion years ago [1,2].

As often occurs with scientific discovery, however, these ideas have raised more questions than they have answered. For example:

- The Giant Impact theory proposes that the Moon formed as a result of a collision between a large protoplanet and the growing Earth [3,4]. Although the idea that the Earth-Moon system owes its existence to a single, random event was initially viewed as radical, it is now believed that such large impacts were commonplace during the end stages of terrestrial planet formation (e.g., [5,6]). Sophisticated numerical models suggest that a giant impact can indeed produce a disk of rocky/vapor material orbiting the Earth. However, we do not yet know whether such a disk can evolve into the Moon observed today, particularly given the existence of significant volatile reservoirs in the lunar mantle.
- The Late Heavy Bombardment (LHB) refers to a period ~4.0-3.8 Ga during which several large lunar basins formed. The nature of the LHB is debated: one view is that the LHB marked the end of a steadily declining bombardment from remnants of planet accretion [7]. Another proposes that the LHB was a short-lived "cataclysm" of dramatically increased impact rates [8], and still another proposes that large basin formation was continuous or episodic throughout the period 4.5-3.8 Ga [9]. We are still unable to observationally distinguish between these three fundamentally different models. The NRC [1] report ranks testing the cataclysm hypothesis and constraining the early lunar impact record as its two top science goals.
- While fundamental questions remain, we believe that over the last decade, there has been a revolution in our understanding of the origin of the Solar System. Theoretical and computational breakthroughs make it possible to realistically model the Moon-forming impact on the proto-Earth and to track the collisional and dynamical evolution of planets and small bodies for billions of years to evaluate the lunar and Solar System bombardment history, and its subsequent differentiation and evolution. In addition, significant improvements in laboratory techniques for dating and analysis of rocks, coupled with improvements in crater counting due to digital image processing, allow us to better assess the compositions and ages of lunar terranes, and to understand their origins and relationships to the deep lunar interior.

With these gains in hand, we now stand on the brink of new fundamental insights into the formation and evolution of the Moon. However, the implications of further lunar exploration go far beyond the Moon as constraints on the lunar origin and evolution can also be used to constrain Solar System evolution. If the Moon is given a high priority by this decadal survey, we will be able to address high priority lunar and broader Solar System science questions, which have significant traceability to planning documents from the 1980's to the present (e.g., [1,2, 10-18]). The Moon can also be used to develop mission-enabling technologies and protocols for wider Solar System exploration (both robotic and manned). Thus, the Moon holds the promise of being the "Rosetta Stone" for understanding the evolution of the Solar System as a whole.

Many “Solar System” science objectives can be studied in more detail on the Moon with human-robotic partnerships than they can elsewhere because of the largely pristine exposures on the Moon and ease of operations there, relative to more distant locales. Therefore, we need to use the Moon to not only understand how the Moon and the Solar System have evolved, but also in understanding how to keep humans safe in space and develop exploration and safety systems so that human Solar System exploration can become a reality. In doing so, the major inner Solar System science questions can be addressed through lunar exploration and this adds to the designation of the Moon as the “Rosetta Stone” for Solar System science exploration.

Here, the main science objectives are outlined and their applicability to better understanding the solar system (and in some cases, beyond) are briefly described. This white paper does not advocate any specific missions or mission types, but emphasizes the unique opportunity lunar science affords for studying the Solar System. It does highlight specific lunar white papers that go into more detail about the subjects than is possible in this contribution.

Understand the Formation of the Moon and the Earth-Moon System

The origin of the Moon within the Earth-Moon system is one of the most fundamental questions in planetary as well as lunar science. The giant impact hypothesis suggests that the Moon formed from debris ejected during a collision between a roughly Mars-sized protoplanet and the growing Earth [3,4]. The giant impact hypothesis is favored over others because it provides a compelling explanation for key traits of the Earth-Moon system, including its angular momentum, the lunar mass and low iron content (e.g., [19-21]).

Despite advances in modeling since the hypothesis was proposed, a self-consistent model linking the impact, the evolution of the disk of material launched into Earth orbit, and the fully formed Moon has not been developed, and several lines of evidence are still difficult to reconcile with the giant impact hypothesis. *In other words, although we know it is possible to a make a moon via a giant impact, we do not yet know whether this model completely describes the formation of our Moon* and several lines of evidence are still difficult to reconcile with the giant impact hypothesis. Quantitative, predictive models for events occurring between the impact and the Moon's accretion are needed to determine whether the hypothesis can be reconciled with key geochemical and geophysical traits. For example:

- The Earth and Moon are compositionally different but isotopically similar. Numerical simulations indicate the Moon should be composed primarily of projectile material. If this is so, why did the material in the protolunar disk acquire the isotopic signatures of our Earth? It is possible the impactor and protoearth formed with identical isotopic signatures, but this appears to be unlikely given our current understanding of planet formation processes. Another possibility is that mixing between the disk vapor and Earth's atmosphere allowed isotopic equilibration after the impact [22]. Although this scenario is intriguing, it has yet to be fully modeled and tested.
- If the Giant Impact occurred, we have isotopic tools to constrain when it occurred. The degree to which we can constrain the timing of the Giant Impact depends on advances in analytical instruments and on the suitability of the samples available for analysis. Lunar meteorites give valuable data, but are not selected specifically for isotopic analyses. Carefully selecting and returning lunar samples to address this is critical. The Earth-Moon system is the only planet-satellite pair from which samples can be obtained to answer the question of when in solar system history such planetary scale impacts were occurring.
- Since the Apollo era, it was thought that the Moon's mantle was anhydrous as its crustal material. Recent water content estimates of the interiors of lunar volcanic glass beads, however, suggest that the lunar mantle may contain up to several hundred parts-per-million

water [23]. At present it is not known to what extent a moon formed from an impact-generated disk can retain water, but it is important to understand the volatile inventory of the Moon to test predictions from the giant impact hypothesis.

- Samples brought back from the lunar surface indicate that the Moon experienced a magma ocean shortly after formation. The extent of melting, however, is unknown; did it include the upper several hundreds of kilometers or did the entire Moon melt? Understanding this may give us insights into the nature of the protolunar disk and how long the Moon took to form. If the Moon formed by collision, when the earth was about 70% accreted, we have a marker during the Earth's accretion. Study of the Moon may allow us to identify whether the Earth's subsequent accretion and evolution is inextricably coupled to the Moon's formation.
- The lunar surface captures the Solar System "climate" affecting the Earth-Moon system, which has been bombarded with asteroidal and cometary debris. The frequency (or even cyclicity) of these collisions is poorly preserved on the Earth. Lunar samples, however, provide a record of the nature of this flux through time, including periodic/episodic storms. In addition, the solar and galactic flux through time is poorly known. The lunar samples likely contain clues about the changing radiation flux through time. The earliest records would help understand how evolution of our atmosphere and life was affected by such changes.

Understand the impact process, and
Understand the impact history of the inner Solar System as recorded on the Moon

As the Moon lacks a substantial atmosphere, meteoroids impact the lunar surface unimpeded and the craters thus produced are only eroded only via other impacts (both micro- and macro-meteoroid). Ages of Apollo samples and lunar meteorites demonstrate that many of the impacts are ≥ 3.5 billion years, with an apparent cluster at 3.9-4.0 Ga (the LHB). The impact process can, therefore, be better understood by examining lunar craters that are much better preserved than their terrestrial equivalents. The lunar cratering rate is extrapolated other planetary surfaces using modeled crater production functions in order to estimate ages for planet surfaces without surface samples. However, the lunar cratering flux (based upon Apollo samples) still needs to be constrained by sampling specific impact basins, both older and younger than the terminal cataclysm. Constraining the lunar cratering rate anchors the inner Solar System cratering rate and provides more precise age constraints for other planetary surfaces. In addition, the lunar cratering rate may also be used to monitor conditions on the Earth at a time for which the evidence on Earth is essentially absent, but important things (e.g., the origin of life) may have been occurring. White papers entitled "Lunar Bombardment History" and "Exploring the Moon and Solar System Impact History with Samples from and Investigation of the South Pole-Aitken Basin" have also been submitted to the Inner Planets panel and contain more details of these topics.

Characterize the environment & processes in lunar polar regions & in the lunar exosphere.

Data from the Lunar Prospector and Lunar Reconnaissance Orbiter neutron spectrometers indicate enhanced hydrogen in the polar areas. Whether the hydrogen is broadly distributed over the polar regions or sequestered in the permanently shadowed craters remains unknown. The H may be in the form of water ice (recent mission results would seem to support this), and they may contain other volatile compounds whose compositions and isotopes will provide a record of their origin (e.g., comet impacts, solar wind flux, degassing history of the Moon). In addition, the current contents of the deposits have been influenced by migration processes in the lunar exosphere and have been affected over time by space weathering. In addition to the immediate scientific benefits of characterizing polar volatile deposits, there are also long term benefits. Any water ice deposits represent a significant resource that would enable scientific exploration. In the short term it will enable scientific exploration of the Moon itself, possibly permitting longer expeditions earlier in an exploration plan. Longer term, volatile deposits can be converted into rocket propellant, enabling scientific exploration further out into the Solar System. The importance of the Lunar Atmosphere and Dust Environment Explorer (LADEE) cannot be underestimated as it will determine global density, composition and time variability of the highly tenuous lunar atmosphere, as well as characterize the Moon's dust environment; these are early priorities of the report by the NRC [1]. Understanding the basic processes in a non-collisional atmosphere will allow us to better understand the thicker atmospheres of Mars, Venus, etc. Investigation of polar H deposits has potential applications to Mercury, with possible presence of H-rich deposits detected by Earth-based radar studies in permanently shadowed regions. Understanding how to sample, analyze and even return such samples has implications for sample return from the Martian poles and comets. Study of the lunar exosphere is important for understanding such surface phenomena on Mercury, other planet moons, asteroids, etc. The white papers entitled The Lunar Dusty Exosphere: The Extreme Case of an Inner Planetary Atmosphere", and "Lunar polar volatiles and associated processes" have been submitted to the Inner Planets panel and contain more details on this issue.

Understand the dynamical evolution and space weathering of the regolith, and
Regolith as a recorder of extra-lunar processes

Lunar regolith contains a wealth of information regarding regolith formation on airless bodies (including asteroids); that information is also critical for in situ resource utilization (ISRU). Understanding the nature of the lunar prospect as it relates to ISRU and all the possible processes we need to test and understand, is actually a scientific problem (applied science) and one that should not be ignored. Regolith maturity varies as a function of exposure to the space environment (solar and cosmic radiation, micrometeorite bombardment). This exposure history has implications for understanding how the Sun's radiation has varied over time if datable regolith horizons can be found (e.g., regolith buried by pyroclastic eruptions; between two dateable lava flows). Such data can then be correlated with terrestrial climate data to evaluate if variations in the Sun's output can be equated with terrestrial climate change. A white paper entitled "Lunar Helium-3 Fusion Resource Distribution" submitted to the Inner Planets panel contains more details on these science objectives.

Understand lunar differentiation, and
Determine the stratigraphy, structure, and geological history of the Moon

Differentiation of the Moon ended ~3.5-3.0 billion years ago when the lunar heat engine was dramatically waning. Examining the internal structure and composition of the lunar crust, mantle and core will allow a strong test of the Lunar Magma Ocean model for terrestrial planet differentiation. A white paper entitled "The Rationale for Deployment of a Long-Lived Geophysical Network on the Moon" has been submitted to the Inner Planets panel and contains details behind exploring the internal structure of the Moon. In addition, white papers entitled "Determining the Origins of Lunar Remanent Crustal Magnetism", "The Lunar Swirls", "Sampling the Extremes of Lunar Volcanism: The Youngest Lunar Basalts", and "Lunar Science and Lunar Laser Ranging" also relate to these topics.

Development and implementation of sample return technologies and protocols

With the Apollo sample collection having been shown to be unrepresentative of the whole Moon [24] and the lunar meteorites being from "unknown" locations, future lunar sample return is required to answer many fundamental lunar (and solar system) science questions. Robotic sample return will allow investigation of science questions at locations different from those visited by humans and has a direct relevance to addressing high priority lunar science questions. Development of robotic sample return technologies that can be tested on the Moon would also enable sample return from other bodies within the Solar System. Development of technologies for sampling extreme environments (e.g., lunar permanently shadowed craters) will be applicable to a range of destinations, including sample return from comets as well as from Mars polar regions. Relevant white papers submitted to the Inner Planets panel include "Sample Return from the Earth's Moon" and "Developing Sample Return Technologies using the Earth's Moon as a Testing Ground". These document where and how samples should be returned from the Moon.

Understand volcanic processes

As for other objectives, the Moon represents a cornerstone for understanding volcanism because of the preservation of very old basalt units on the lunar surface and it allows investigation of the role of volcanism in early planetary evolution. The Apollo samples and now lunar meteorites demonstrate that volcanism occurred at least as early as 4.35±0.05 Ga and widespread volcanism lasted over 1 billion years before declining, with lava flows emplaced as recently as 1 billion years being identified on the lunar surface on the basis of crater counts. Sampling, bulk and mineralogical analysis, and accurate age determination of these lavas, as well as comparison with known terrestrial and lunar basaltic compositions, will yield important information on the differentiation of the lunar interior. Understanding the spatial and temporal distribution of lunar fire-fountain deposits (i.e., pyroclastics) is critical for understanding the volatile content of the lunar interior. Data on volcanic glass beads, the products of such eruptions, indicate that they were derived from distinct source regions of the mantle (compared to crystalline mare basalts) and still contain a signature of the volatile contents of their mantle sources. White papers entitled "Lunar Domes" and "Sampling the Extremes of Lunar Volcanism: The Youngest Lunar Basalts" have been submitted to the Inner Planets panel on this topic.

Astrophysical investigations using the Moon

The LER describes how the Moon is a unique platform for fundamental astrophysical measurements of gravitation, the Sun, and the Universe. Lacking a permanent ionosphere and, on the farside, shielded from terrestrial radio emissions, a low frequency (≤100 MHz) interferometric radio array on the Moon will be an unparalleled astrophysical and heliospheric observatory. Crucial stages in particle acceleration near the Sun can be imaged and tracked. Evolution of the Universe before (the "Dark Ages") and during the formation of the first stars will be traced using the highly redshift 21-cm HI line, yielding high precision cosmological constraints on a largely unexplored epoch of the universe ($15<z<150$). The lunar farside is likely the only location in the inner Solar System to conduct such sensitive low frequency observations. Lunar Laser Ranging of the Earth-Moon distance provides extremely high precision constraints on General Relativity (e.g., tests of the Strong Equivalence Principle) and alternative models of gravity, and also reveals details about the interior structure of the Moon. A new network of retroreflectors is required beyond that of Apollo and Lunokhod to provide the necessary precision (~10 μm) needed to constrain these models. Relevant white papers entitled "Science from the Moon: The NASA/NLSI Lunar University Network for Astrophysics Research (LUNAR)" and "The Moon as a Test Body for General Relativity" have been submitted to the Inner Planets panel.

Heliophysical Investigations using the Moon

A number of high priority heliophysics investigations are defined in the LER. As already noted, the Moon presents a unique environment in which to study fundamental solar system processes. The lunar surface and its unique crustal magnetic fields are constantly exposed to both plasma and photons. Over crustal fields, the resulting interaction forms possibly the smallest magnetospheres in the solar system, potentially shielding portions of the surface from solar wind weathering and volatile implantation. Over the rest of the surface, the constant plasma and photon bombardment acts to produce much of the tenuous lunar exosphere, and also to electrify the surface, producing electric fields that may couple to the lunar dust environment. These processes are ubiquitous in the solar system, and thus their study has fundamental science implications, as well as potential benefits for exploration of the Moon and other airless bodies. Other important science goals, also potentially benefiting both science and exploration, include radio astronomy from the Moon and characterization of the lunar radiation environment.

Use the Moon as a platform for Earth-observing studies.

Long-term observations of the whole Earth disk from the Moon provide a broad picture of annual fluctuations in atmospheric composition and, over several years, can map trends in these fluctuations. The high priority Earth Observing investigations include: Monitor the Variability of Earth's Atmosphere, Detect and Examine Infrared Emission of the Earth, Develop Radar Interferometry of Earth from the Moon, E/PO Opportunities Enabled by a Lunar-Based Earth Observatory (LBEO), and Lunar-Based Earth Observatory Demonstration.

SUMMARY

A coordinated lunar science exploration plan allows for significant progress to be made in our understanding of the Moon and also the Sun, Earth, Solar System, and beyond (see also the white paper entitled "Calming the Gathering Storm with a Long Term Lunar Program"). The topics briefly outlined above demonstrate the relevance of the Moon as a "Rosetta Stone" for Solar System science and further demonstrate that Solar System science can be done by studying the Moon in situ with human and robotic systems as well as remotely with robotic spacecraft.

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