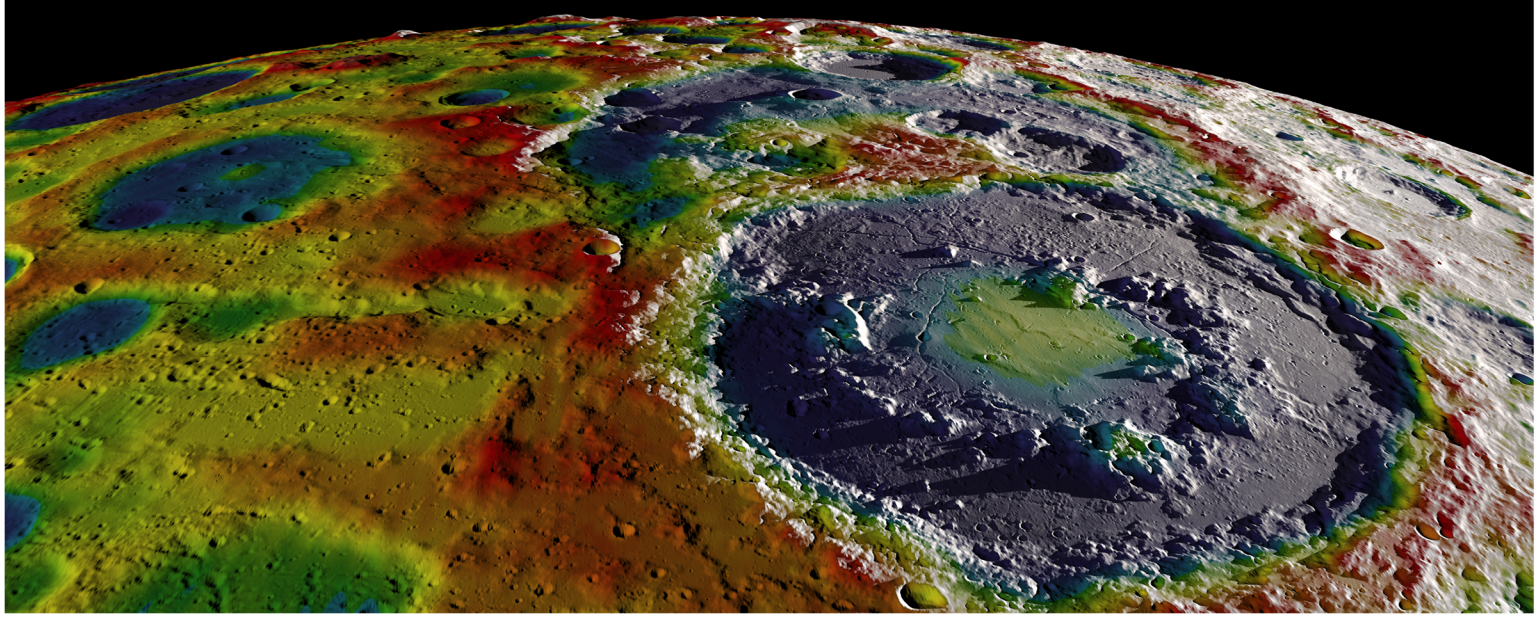
TRANSFORMATIVE LUNAR SCIENCE

Recommendations from scientists of the
Solar System Exploration Research Virtual Institute (SSERVI)

Principal Contributors:
Dr. Carlé M. Pieters [Brown University]
Dr. Robin Canup [Southwest Research Institute]
Dr. David Kring [USRA Lunar and Planetary Institute]
Dr. James W. Head, III [Brown University]
Astronaut David R. Scott [Apollo 15 Commander]

Prepared: January 2018

The accessible differentiated cousin of Earth



Transformative Lunar Science

1. Introduction

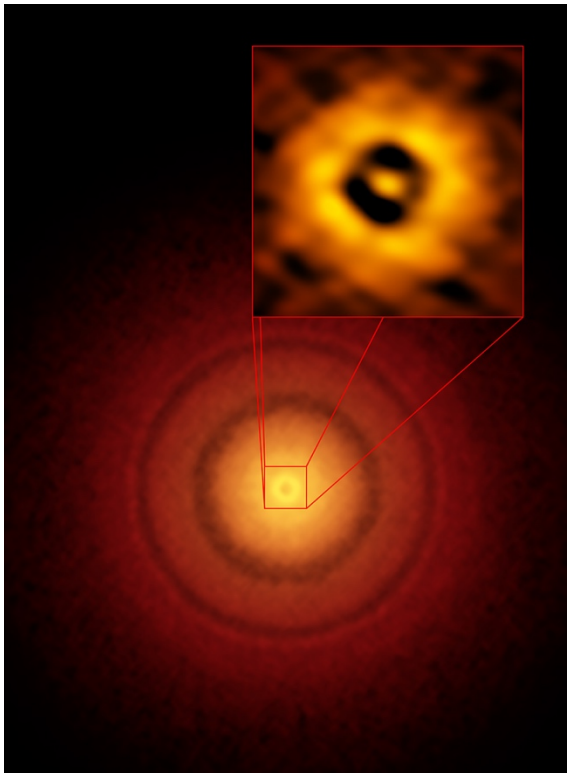
This 'white paper' provides a response to the question *What **transformative lunar science** issues can/should be addressed in the currently evolving space science era?* This question targets the most important opportunities and the potentially greatest scientific payoffs from future space exploration associated with the Earth-Moon system. We provide several diverse examples of fundamental science questions that NASA can/should address through new lunar exploration initiatives. We recognize that the present is an entirely different period of human history than the one that initiated and implemented the previous major lunar undertaking during the Apollo Lunar Exploration Program. Current issues and concerns focus more on the need to understand our global environment and the sustainability of life on our planet (and possibly elsewhere) in the context of evolution of the Solar System and universe. Exploration beyond Earth is an essential part of our future and examples below illustrate how the Moon provides a cornerstone for that endeavor.

2. Example Transformative Lunar Science

2a) Establish the period of giant planet migration and its effects in our Solar System

There is now broad agreement that our giant planets migrated over large distances early in their history, based on their orbital eccentricities and inclinations, the observed structure of the Kuiper Belt, and new data from exoplanetary systems. At least one period of migration was driven by interactions between the giant planets and remnants of the outer proto-planetary disk. As the giant planets migrated to their current orbits, previously stable reservoirs of materials became destabilized, causing enhanced rates of bombardment throughout the Solar System.

The timing of giant planet migration remains a central open question. Two models involve either 1) early planet migration and a bombardment rate that declined with time in a relatively smooth manner, or 2) late migration, in which a temporal delay between planet formation and migration resulted in a discrete "late heavy bombardment" (LHB) episode some 400 to 600 Myr after the Earth-Moon system formed. Distinguishing between these scenarios provides critical constraints on the accretion and orbital histories of the giant planets, the mass and extent of planetesimal disks in the inner and outer Solar System (asteroid belt, Kuiper Belt), and the impact bombardment of all Solar System bodies during the first half-billion years of Solar System history. These are fundamental issues to understanding our Solar System's origin, the structure of exoplanetary systems and disks, and the development of habitable and potentially habitable environments.



ALMA [2016] 870 μm data of TW Hya proto-planetary disk highlighting the evolving distribution of small particles around the young star. Centermost gap is at ~ 1 AU.

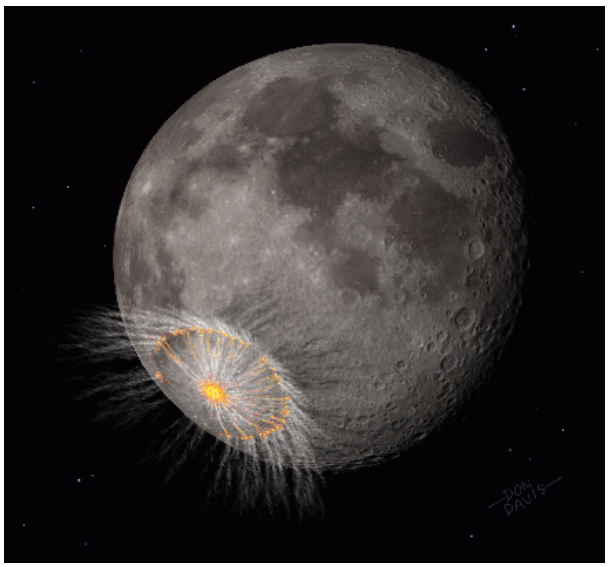
Understanding early heavy bombardment also has profound astrobiological implications. The origin of life on Earth must have been strongly affected, if not catalyzed, during these violent periods and quiet interludes. The timing of such Solar System bombardment periods would have strongly affected Mars during its

early evolution when it shows evidence for a thicker atmosphere and abundant surface water.

The Moon's ancient terrains and rocks retain a record of our Solar System's earliest bombardment history and, therefore, can constrain the timing of giant planet migration and heavy bombardment of the inner Solar System. However, the Apollo samples are believed to be dominated by ejecta debris largely from a single event, formation of the enormous nearside Imbrium basin, which occurred late in the basin forming period at ~3.9 Ga. Sampling impact melt from and determination of the ages of large basins, from the youngest (Orientale, Schrödinger) to middle aged (Nectaris) and the oldest (the gigantic South Pole-Aitken, SPA), will distinguish fundamental processes (primordial *vs.* late giant planet migration bombardment) through which the giant planets shaped the character of the terrestrial planets early in Solar System evolution.

2b) Provide an absolute chronology for Solar System events

After the basin-forming epoch of the first billion years, the Earth, Moon, and all other Solar System bodies continued to be targets of wayward asteroids and comets. The number of accumulated craters is directly related to the age of the surface. Sometimes those impacts produced dramatic results, such as the geologically recent collision that excavated the Chicxulub impact crater and extinguished much life on Earth, including dinosaurs, 66 million years ago. Since the Earth's early geologic record has been largely erased, the Moon is the best preserved and most accessible place to constrain the ages of events that occur on planetary surfaces (chronology) by combining the frequency of craters accumulated over time with measured absolute sample ages.



Depiction of Tycho crater formation (est. at 100 Ma). *SWRI*

Lunar sample measurements are the basis for solid body chronologies used across the Solar System. However, the Apollo sites provide absolute ages for an extremely limited range of terrain on the lunar nearside. At present a large discrepancy exists between impact flux models, with inferred ages differing by up to a billion years in the 3.5 Ga to 2 Ga time period. Fluxes are also very poorly constrained for the last billion years due to lack of data. Removing such chronological discrepancies is key to understanding impact rates as life was evolving on Earth as well as when Mars was potentially habitable. Documenting the recent flux record on the Moon would provide important constraints for the present impact flux environment at 1 AU, of great interest for human civilization.

Determining the ages of samples from a suite of carefully selected presumed young lunar terrain and impact craters of varied sizes and stratigraphic ages would allow us to develop an accurate clock to be applied to planetary surfaces throughout the Solar System. Ages from 1 to 3 Ga terrains, *e.g.,* near-side young basaltic terrains and large craters like Aristillus and Tycho, would address the time period during which available chronologies are highly uncertain. Accurate absolute ages would also enable testing of postulated impact flux spikes (*e.g.,* 0.47, 0.8, 1.4 Ga, ~ 2 Ga) that appear to be coincident with major changes in Earth's biosphere.

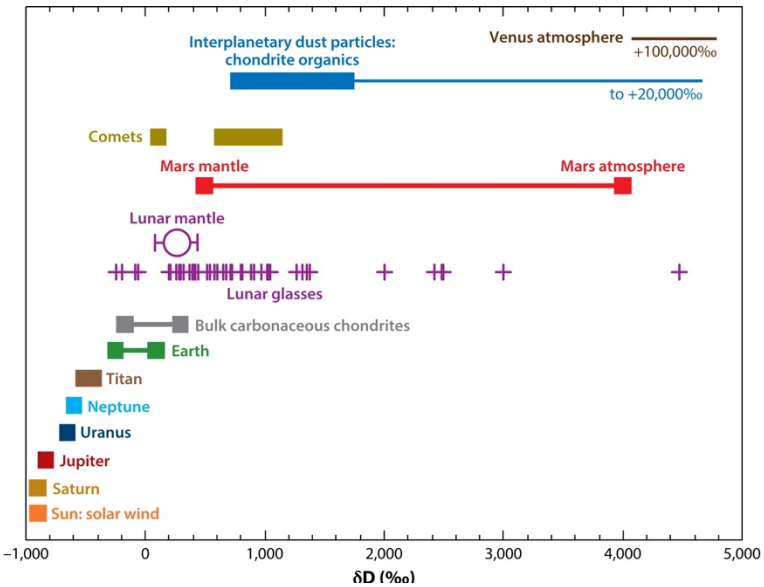
2c) Use the accessible vantage from the lunar farside to view the universe

Twenty-seven missions have reached the surface of the lunar nearside. None have reached the farside (yet). Landing site studies of that vast unexplored territory indicate it is a tremendous

land of opportunity in which many of the scientific objectives of lunar exploration can be addressed. While the focus of much current work is on how unexplored lunar terrain can address Solar System science, it is also evident that the farside can be used as a unique astrophysical platform for probing the building blocks of the Universe's earliest galaxies that formed during an epoch described as cosmic dawn. Because the farside is naturally shielded from near-Earth interfering signals, it offers perhaps the best location in the inner Solar System to examine the initial products of the Big Bang through extremely sensitive measurements made by low frequency radio telescopes.

2d) Understand and utilize the special water cycle of the Moon and other airless bodies

The concept of water (H_2O and/or OH in several forms) on airless bodies of the inner Solar System became very real with surprising discoveries that began less than a decade ago and involve the Moon, Mercury, and asteroids. Sources of observed water on these bodies are 1) internal [primordial; endogenic processes], 2) external [delivery by asteroids and comets], and 3) *in-situ* [created on the surface by interactions with the solar wind plasma]. Water was confirmed to be sequestered at the poles of Mercury by the MESSENGER mission and almost certainly represents external materials that have accumulated in permanently shadowed polar areas over time. In contrast, mid-latitude areas on the large main-belt basaltic asteroid Vesta exhibit small amounts of localized hydrated materials as examined by the Dawn mission. This water is also believed to be foreign to the body and represents remnant contamination by primitive hydrous carbonaceous chondritic impactors. The largest asteroid Ceres, also mapped by Dawn, is a low-density dwarf planet derived from ice and silicates. Ceres' near-surface contains abundant endogenic hydrated materials but only minor amounts of exposed water-ice, including small amounts of apparently mobile frost that accumulates in a few persistently shadowed regions at the poles, similar to that seen at Mercury.



Diagnostic D/H measurements of Earth, meteorites and comets, and lunar samples compared to other Solar System bodies. *Hauri et al., 2017*

The Moon is now known to host all three forms of Solar System water [endogenic, sequestered external, and *in-situ*], but understanding the concentration, evolution, and interrelated dynamics of these varied sources of water, i.e. the 'lunar water cycle', is *in its infancy*. Primordial water in some Apollo samples was measured with sensitive laboratory tools starting in 2008 and has been inferred to indicate initial water contents comparable to that of Earth's mantle. Abundant water has long been predicted to be sequestered at the lunar poles similar to that found at Mercury. However, measurement has eluded most previous sensors except directed impact excavation in 2010 by NASA's LCROSS mission and later measurements at UV wavelengths from NASA's LRO mission. Lunar polar water is now thought to be largely buried. The unexpected independent detection of global surficial *in-situ* water in 2009 by three of NASA's near-infrared imaging spectrometer assets indicates a fundamental and previously unrecognized interaction between geology (silicate rocks) and space physics (plasma from the Sun).

More advanced sensors placed both in orbit and on the surface would allow spatial and temporal characterization of this water and would probe how the three forms interact in the natural lunar environment. Modern analytical tools in Earth-based laboratories are now sensitive enough to analyze and compare trace elements and isotopic compositions for carefully selected returned samples. An integrated campaign directed toward utilizing a combination of new modern remote sensing and *in situ* tools as well as sample return data is certain to resolve many of the current dilemmas about the character and origin of water on the Moon and throughout the inner Solar System. It will also inevitably open new questions yet to be posed.

2e) Characterize the Moon's interior to reveal how this differentiated neighbor of Earth formed and evolved

The Earth and Moon were forged from the same mega-impact that resulted in the Earth-Moon system. Our massive Moon minimizes Earth's obliquity and associated climatic variations, thus allowing persistent oceans. On planet Earth we can readily study the enormous diversity of crustal materials and through them develop an understanding of geologic events and processes involved during Earth-history. To evaluate the interior, however, we rely largely on samples brought to the surface through magmatic events or deep-seated eruptions and on an expanding array of modern seismic stations around the world. With the Moon we have the opportunity to evaluate the interior of a smaller differentiated planetary body that is directly related to Earth and our planet's accretion, but that has not been rearranged by plate tectonics.

Analyses of samples from the lunar mantle would transform our understanding of the Moon's composition and the nature of the Earth-Moon forming event. No such samples are known to exist in current collections, but they could be obtained from regions excavated by large impacts like SPA with specific targets identified using modern remote sensors. In addition, samples from pyroclastic deposits from deep-seated sources would clarify the portion of the Moon that was volatile-rich, and to what extent the Moon's early water had the same isotopic composition and implied source as Earth's water. On a global scale, however, knowledge of the Moon's interior structure could readily be obtained from an array of modern seismic stations. Allowing comparisons with Earth, such unique data would provide a quantum leap in understanding the character and evolution of planetary interiors. Furthermore, broad issues such as constraints on the Moon's initial thermal state, lunar upper mantle evolution, relaxation after basin formation, and why the Moon's crust is so much thicker on the farside than on the nearside could also be resolved.

2f) Evaluate the extended record of space weather and fundamental processes of plasma interactions with surfaces

As returned soil samples from Apollo and Luna missions have been analyzed with increasingly sophisticated tools in Earth-based laboratories, it has become recognized that they record a plethora of events ranging from solar wind products accumulating on individual grains to the cumulative tracks of galactic cosmic rays buried in the soil. The constant rain of Solar System dust (micro-meteorites largely carbonaceous chondrite particles) stirs the soil and reprocesses grain surfaces. The ~5-10 m thick fine grained regolith has accumulated these events over billions of years. Deriving the history of solar weather over this interval would allow us to glean insights into a wide range of Solar System questions (e.g., the evolution of the Sun, the loss of Mars's atmosphere). The fragile structure of the uppermost surface of the natural lunar regolith (informally called 'fairy-castle') is likely to be linked to electrostatic processes; although it has never been measured, its destruction has been documented at landed sites. The sensitivity of both modern *in-situ* instruments and available laboratory analysis tools make a concerted effort to evaluate the present space environment and its history recorded in accumulated lunar regolith not

only viable but exceptionally valuable for both the science and the engineering aspects of lunar exploration. The lunar surface provides an exceptional laboratory to study the physics of interactions of flowing plasmas with planetary bodies (both with/without magnetic fields), processes that are of great interest in both space and basic plasma physics, and are now recognized as leading to the mobilization, transport, and possibly even the removal of fine dust on all airless planetary bodies.

3. Moving forward with NASA Science and Exploration

The United States dominated the first half-century of the Space Age with its fundamental leadership in human and robotic exploration that provided inspiration and infused a huge technological boost to the United States and its economy. The successful Apollo Lunar Exploration Program created an enormous sense of pride and prestige across our nation and around the Earth. A very tangible outcome of this leadership was the inspiration that it provided for generations of American youth and the motivation to enter careers in science, engineering, and innovation. The success of NASA's early lunar program has become the model that space-faring nations around the world are aggressively emulating today. We outline key steps forward for NASA Science and Exploration to make in order to realize comparable success from *Transformative Lunar Science* in the years ahead.

3a) Achieve Global Leadership in lunar exploration

Over the last decade Japan, India, China, Russia, ESA, and now Korea and other nations have demonstrated individual capabilities and plans for extensive lunar exploration (orbital, in-situ, rover, and human sortie). The proposed Google X-Prize stimulated commercial enterprises to produce serious plans for lunar landers and rovers. In the near future the Earth's Moon will likely be the proving ground for abundant national and private endeavors.

What is the role of the United States and its unparalleled (but increasingly challenged) human and robotic capabilities and expertise to be? The current administration recently directed NASA to make plans for renewed American involvement in lunar exploration, including "boots on the ground", and the Vice President and the National Space Council are assertively following this direction. If the United States is to continue its rich history of national and international leadership in space, we must seize the unique opportunity that the Moon affords in this part of the evolving Space Age. Equally clear is that lunar exploration leadership within the expanding international community represents a unique opportunity for the United States and NASA to synergistically bring together their fundamental programs in human exploration, scientific exploration, technological development, and commercial encouragement. We believe that re-igniting and sustaining United States/NASA international leadership in exploration of the Moon is a fundamental requirement to achieve long-term objectives, including exploration of Mars, for the next half century of space science.

3b) Establish a solid lunar exploration infrastructure

Most single spacecraft beyond LEO must operate in a manner similar to the covered wagons of our early settlers; take *everything* with you! This is expensive, redundant, carries increased risk, and reduces the capabilities of the payloads. NASA could provide leadership in the international arena for a wide array of lunar infrastructure concepts, ranging from a long-lived global communications/GPS network with high bandwidth (in addition to science needs, HD color video is essential to retain the current generation), to expanding complex delivery of international crews to lunar orbit and the lunar surface (Orion, Space Launch System), and to station-keeping and telerobotic capabilities of a Deep Space Gateway model.

3c) Coordinate planning and implementation of human/robotic partnership

Two generations ago, astronauts of the Apollo Lunar Exploration Program demonstrated unequivocally the crucial role that human explorers can play on the lunar surface in optimizing scientific return and mission operations. In the ensuing half-century, advances in robotic diversity and technology, artificial intelligence, telepresence, miniaturization, and access to extreme areas, have rewritten the script for human exploration, defining new roles and capabilities for both humans and robots. This characterizes a new human and robotic partnership as we return to the Moon and on to Mars and other Solar System destinations. The Moon provides a natural, yet challenging, environment for initial use of this next generation of human/robotic exploration capabilities, while placing NASA and the US in the leadership position for 21st century exploration. Even with current lunar science data in hand, valuable Design Reference Campaigns are being developed to address several of the above Transformational Lunar Science examples using the anticipated significantly enhanced modern human/robotic partnerships.

3d) Optimize commercial involvement

If left uncoordinated, the plethora of independent national, international, and commercial missions to the Moon could become a logistical nightmare with huge waste of fiscal and intellectual resources. The current success of companies such as SpaceX is due to the monopsony market situation; NASA and other federal agencies are usually the only buyers. A multi-component U.S. NASA-led lunar exploration program should carefully define near- and long-term exploration goals and science objectives that will enable commercial entities to identify opportunities, articulate viable business plans, and develop appropriate skills and technologies for success.

In summary*: A strong United States/NASA-led International Lunar Exploration Program would not only demonstrate continued leadership of the United States and garner attendant pride and prestige, but would also develop the international and commercial partnerships that would help prepare and propel the next great exploration endeavors beyond the Earth-Moon system.*

APPENDIX:

Contributors to this report are scientists brought together through NASA's Solar System Research Virtual Institute (SSERVI) which focuses on issues related to the Moon, asteroids and moons of Mars as future destinations for NASA. References/bibliography for material discussed in the text can be provided on request. As additional background, we provide brief summaries of National Research Council studies that discuss priorities of missions assessed within planetary science decadal reports (2003, 2011) as well as a detailed evaluation of the science context for exploration of the Moon (2007).

National Research Council (2003) *New Frontiers in the Solar System: An Integrated Exploration Strategy,* Natl. Acad. Press.

National Research Council (2007) *Scientific Context for Exploration of the Moon*, Natl. Acad. Press.

National Research Council (2011) *Vision and Voyages for Planetary Science* in the Decade 2013-2022, Natl. Acad. Press.

NRC Decadal Reports in Planetary Science (2003, 2011)

As Apollo came to a close, NASA-directed planetary science 'Flagship' missions (large, expensive, > several B$) focused principally on Mars and the outer solar system. To accommodate the most compelling science for the rest of the Solar System, two forms of missions to be openly competed through a peer-review process were developed and intended to be implemented on a regular cadence: (1) New Frontiers (intermediate cost, now ~1B$) and (2) more frequent Discovery (low cost, now ~500M$). NRC decadal reports prioritized Flagship and New Frontier mission class science objectives. Since the science merits of low cost Discovery concepts depend greatly on the specific mission details, these are normally prioritized during the peer-review process of proposals received.

Two New Frontiers class Solar System science priorities identified in the NRC 2011 decadal report 'Vision and Voyages for Planetary Science' target the Moon for strong scientific reasons. The first, South Pole-Aitken Basin sample return, requires landing on the lunar farside; this sample related science-driven mission was also named the top priority in the earlier NRC 2003 decadal report (after exploring the Kuiper Belt and Pluto). The second New Frontiers class activity, a distributed lunar geophysical network, requires multiple landing sites and has sparked strong interest and support across the international community.

A. South Pole-Aitken Sample Return:

The expanding documentation of diverse planetary systems in our part of the galaxy requires revision of models for the formation and early evolution of our Solar System; once formed, major planets interact and migrate redistributing material. For our own Solar System, whether such reorganization occurred in one or several periods (and when) is a fundamental constraint on the character and evolution of the terrestrial planets, including Earth. The continuous impact record retained on the Moon provides an accessible means to date these early events. Documented samples from the enormous South Pole-Aitken basin, the *oldest* and *largest* impact basin on the Moon, will date the beginning of the basin forming period at 1 AU. This is an essential constraint on the 'late heavy bombardment' period (gradual or narrow pulse) that shaped all the terrestrial planets and controlled when a period of 'habitability' began.

B. Lunar Geophysical Network:

As the smaller element of the Earth-Moon system, the Moon provides insight into evolution products and processes of a small terrestrial body. Most of the surface represents the crust (including rearrangement by impacts), but to understand the structure and character of the interior requires geophysical techniques. LRO and GRAIL have provided exquisite topography and crust/mantle gravity (density) variations respectively. As on the Earth, seismic probing of the lunar interior is essential to evaluate the actual structure of the crust, mantle, and core of this small terrestrial body. Technology has advanced enormously during the ~50 years since Apollo, as has understanding of the requirements for a geophysical network specifically designed for the broad science return that can be harvested on the Moon through a well-placed network of coordinated modern sensors.

NRC Scientific Context for Exploration of the Moon (2007)

This document explicitly describes major Solar System science objectives enabled through Lunar Science themes. It identified eight prioritized science concepts and 35 related goals. The top four concepts relate to Solar System bombardment history uniquely revealed on the Moon, the structure and composition of the lunar interior as a small differentiated planetary body, the diversity of lunar crustal rocks yet to be identified, and the special environments at the lunar poles. The concepts laid out in this report remain valid and are currently being updated by a Special Action Team [SAT] initiated by the Lunar Exploration and Analysis Group [LEAG] and will be available soon. Several new science highlights are recognized as a result of the last decade of small missions to the Moon by the international community and include understanding the three important components of the recently recognized 'water cycle' found on the Moon and fundamental insights into the origin of the Earth-Moon system as recorded in ancient lunar rocks.