The Scientific Context for Exploration of the Moon: Interim Report

Committee on the Scientific Context for Exploration of the Moon, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

The Scientific Context for Exploration of the Moon–Interim Report

Committee on the Scientific Context for Exploration of the Moon
Space Studies Board
Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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[1] During committee deliberations, recused himself from discussion of the finding and recommendation related to the South Pole-Aitken basin.

[2] Resigned from the committee August 11, 2006, because of other commitments.

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Preface

As an initial part of the newly established Vision for Space Exploration, NASA is aggressively defining and implementing a series of robotic orbital and landed missions to the Moon, through the Lunar Precursor and Robotic Program (LPRP) of the Exploration Systems Mission Directorate (ESMD). The LPRP is intended to obtain essential supporting data for robotic and human landings planned for 2018 and shortly thereafter. The first LPRP mission, the Lunar Reconnaissance Orbiter, is already in implementation and scheduled for a 2008 launch. A second mission, a lander, is in pre-formulation. The LPRP program office is currently developing an overall LPRP program architecture. In order to realize this benefit from the LPRP series, NASA needs a comprehensive, well-validated, and prioritized set of scientific research objectives for the Moon. The purpose of this interim report is to provide scientific input to NASA's planning process, with a full report to follow in summer 2007.

Looking beyond the robotic precursor missions, science goals need to be articulated for early decisions about system design and operations planning for combined robotic and human activities on the Moon. For a longer-range human presence on the Moon, the scope of science is potentially broader, possibly including emplacement or assembly and maintenance and operation of major equipment on the lunar surface. After a multi-decade hiatus in major lunar science and exploration activities, the first decade of the 21st century will be marked by a major resurgence in lunar missions and high potential for scientific return.

This study was initiated at the request of Mary Cleave, NASA's associate administrator for science, to Lennard Fisk, chair of the Space Studies Board (SSB), in a letter dated March 13, 2006, asking the National Research Council (NRC) to provide guidance on the scientific challenges and opportunities enabled by a sustained program of robotic and human exploration of the Moon during the period 2008-2023+. A revised letter of request was received on June 5, 2006.

In response to this request, the NRC established the Committee on the Scientific Context for Exploration of the Moon. The committee met at the National Academies' Keck Center, Washington, D.C., on June 20-22, 2006, and at the Beckman Center, Irvine, California, August 2-4, 2006, and heard presentations from the following NASA staff, university researchers, and other experts: James Head III, Brown University; Paul Hertz, NASA Science Mission Directorate; Butler Hine, NASA Exploration Systems Mission Directorate; Noel Hinners, Lockheed Martin (retired); Ayanna Howard, Georgia Institute of Technology; Brad Jolliff, Washington University at St. Louis; Gary Lofgren, NASA Johnson Space Center; Clive R. Neal, University of Notre Dame; Charles Shearer, University of New Mexico; Paul Spudis, Johns Hopkins University; G. Jeffrey Taylor, University of Hawaii; and S. Ross Taylor, Australian National University.

The committee also held several teleconference calls and communicated extensively via e-mail among its members while also soliciting input from colleagues selected for their expertise in the various scientific disciplines relevant to the study of the Moon and/or the development and operation of spaceflight instrumentation and robotic spacecraft. In addition, committee members consulted related reports issued by the SSB, some with other boards (listed in the Bibliography).

THE INTERIM REPORT

This interim report was requested by NASA and prepared by the committee. To meet the ambitious schedule set for the interim report, the committee decided to present more detailed and additional material in its full report. The interim report provides a summary of scientific themes evaluated by the committee and related findings and recommendations concerning a broad range of science that should be an integral part of the lunar component of NASA's Vision for Space Exploration. Intended to meet the near-term needs for science guidance for the lunar component of the Vision, the interim report deliberately focuses on the science of the Moon. Issues relating to science from the Moon, as well as a summary of the current state of understanding of the Moon, will be presented and discussed more completely in the full report.

The *primary goals* of the interim report are to:

1. Identify a common set of prioritized basic science goals that could be addressed in the near-term via the Lunar Precursor and Robotic Program (LPRP) of orbital and landed robotic lunar missions (2008-2018) and in the early phase of human lunar exploration (nominally beginning in 2018); and
2. To the extent possible, suggest whether individual goals are most amenable to orbital measurements, in situ analysis or instrumentation, or terrestrial analysis via sample return.

The science scope of study goals 1 and 2 encompasses:

- The history of the Moon and of the Earth-Moon system;
- Implications for the origin and evolution of the solar system generally, including the Sun; and
- Implications of all of these for the origin and evolution of life on Earth and possibly elsewhere in the solar system.

Secondary goals to be considered (see Appendix A) during the course of the study will be addressed in the committee's full report.

In this interim report the committee develops a number of scientific themes describing scientific issues and broad scientific goals as well as ancillary themes that it judges to be of importance in a comprehensive program of lunar research. Included in these descriptions of the scientific themes are discussions of how best to carry out the measurements and other actions required to reach these broad goals. Specific scientific goals, derived from the themes identified by the committee, are then separated into three priority areas that follow from the themes. Findings and recommendations are then derived from these integrated science priority areas. Findings and recommendations for related areas are also summarized.

The views expressed in this report were stimulated and expanded from findings and recommendations presented in previous SSB reports. In particular, the 2003 decadal study, *New Frontiers in the Solar System*, outlined lunar science priorities in the context of the future exploration of the solar system. In addition, the committee asked for and received white papers and consulted widely with colleagues and other experts from the lunar science community. As part of its deliberations, the committee examined the history of lunar science and considered new scientific developments that have occurred since the Apollo 17 lunar mission.

The draft interim report was completed in mid-August 2006 and was sent to external reviewers for commentary. A new draft responding to the reviewers' comments was completed in early September, and the prepublication version was approved on September 13 for release. The full report is planned for release in mid-2007.

ACKNOWLEDGMENTS

The work of the committee was made easier thanks to the important help, advice, and comments provided by numerous individuals from a variety of public and private organizations. In addition to the speakers listed above, the following individuals and groups provided useful input to the committee: David Beaty, Paul Schenker, and Edward W. Tunstel, Jet Propulsion Laboratory; Donald Bogard, Friedrich Horz, John Jones, and Sarah Noble, NASA Johnson Space Center; Jack Burns, Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM); Ian A. Crawford, Birkbeck College, United Kingdom; Lisa Gaddis, U.S. Geological Survey, Flagstaff; Rick Halbach, Lockheed Martin Corporation; Lon Hood, University of Arizona; Dan Lester, University of Texas; Jonathan Levine, University of Chicago; Moon-Mars Science Linkages Science Steering Group of MEPAG (MMSL-SSG); Clive R. Neal, University of Notre Dame; Harrison H. Schmitt, NASA Advisory Council; Charles Shearer, University of New Mexico; Norman Sleep, Stanford University; John Stevens, Lockheed Martin Corporation; Timothy Swindle, University of Arizona; and Lawrence Taylor, University of Tennessee. Also, Bruce Jakosky, Ariel Anbar, Jeffrey Taylor, and Paul Lucey for their paper on astrobiology; Clive R. Neal, Lon Hood, Shaopeng Huang, and Yosio Nakamura for their white paper “Scientific Rationale for Deployment of a Long Lived Geophysical Network on the Moon”; Timothy Stubbs, Richard Vondrak, and William Farrel for “A Dynamic Fountain Model for Lunar Dust”; and contributors too numerous to list in a Lunar Exploration Analysis Group (LEAG) report on lunar science.

The committee also thanks SSB research assistant Stephanie Bednarek for her valuable assistance in assembling the draft of the interim report and assisting at the committee’s meetings.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC’s Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

The committee wishes to thank the following individuals for their participation in the review of this report: Ariel D. Anbar, Arizona State University; Radford Byerly, Jr., University of Colorado; Robert N. Clayton, University of Chicago, Boulder; Pascale Ehrenfreund, University of Leiden; Robert P. Lin, University of California, Berkeley; Mario Livio, Johns Hopkins University; Lawrence A. Taylor, University of Tennessee; Richard H. Truly, Vice Admiral, U.S. Navy (ret.); and Mark Wieczorek, Centre National de la Recherche Scientifique.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Bernard F. Burke, William A.M. Burden Professor of Astrophysics, Emeritus, Massachusetts Institute of Technology. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

We know more about many aspects of the Moon than any world beyond our own, and yet we have barely begun to solve its countless mysteries. The Moon is, above all, a witness to 4.5 billion years of solar system history, and it has recorded that history more completely and more clearly than any other planetary body. Nowhere else can we see back with such clarity to the time when Earth and the other terrestrial planets were formed.

Planetary scientists have long understood the Moon's unique place in the evolution of rocky worlds. Many of the processes that have modified the terrestrial planets have been absent on the Moon. The lunar interior retains a record of the initial stages of planetary evolution. Its crust has never been altered by plate tectonics, which continually recycle Earth's crust, or planetwide volcanism, which resurfaced Venus only half a billion years ago, or by the action of wind and water, which have transformed the surfaces of both Earth and Mars. The Moon today presents a record of geologic processes of early planetary evolution in the purest form.

For these reasons, the Moon is priceless to planetary scientists: It remains a cornerstone for deciphering the histories of those more complex worlds. But because of the limitations of current data, researchers cannot be sure that they have translated the message correctly. Now, thanks to the legacy of the Apollo program, and looking forward to the Vision for Space Exploration, it is possible to pose sophisticated questions that are more relevant and focused than those that could be asked over three decades ago. Only by returning to the Moon to carry out new scientific explorations can we hope to close the gaps in understanding and learn the secrets that the Moon alone has kept for eons.

NASA asked the National Research Council (NRC) to provide guidance on the scientific challenges and opportunities enabled by a sustained program of robotic and human exploration of the Moon during the period 2008-2023+ as the Vision for Space Exploration evolves. This interim report was prepared by the Committee on the Scientific Context for Exploration of the Moon. The committee will present additional material and more details in its full report, to be released in mid-2007.

PRIORITIES, FINDINGS, AND RECOMMENDATIONS

Within a balanced science program the committee provides the following prioritization of lunar science goals that can be accomplished by lunar measurements and analyses during the early phases of the Vision for Space Exploration. It has used the prioritization criteria adopted by the decadal survey *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NRC, 2003) as a guideline: scientific merit, opportunity, and technological readiness. Each of these priorities has related orbital, in situ, returned sample, and human-tended measurement goals.

1. Fundamental Solar System Science
   - Characterize and date the impact flux (early and recent) of the inner solar system.
   - Determine the internal structure and composition of a differentiated planetary body.
   - Determine the compositional diversity (lateral and vertical) of the ancient crust formed by a differentiated planetary body.
   - Characterize the volatile compounds of polar regions on an airless body and determine their importance for the history of volatiles in the solar system.

2. Planetary Processes
    - Determine the time scales and compositional and physical diversity of volcanic processes.
    - Characterize the cratering process on a scale relevant to planets.
    - Constrain processes involved in regolith evolution and decipher ancient environments from regolith samples.
    - Understand processes involved with the atmosphere (exosphere) of airless bodies in the inner solar system.

3. Other Opportunities (additional information is required for these)
    - Utilize data from the Moon to characterize Earth's early history.
    - Determine the utility of the Moon for astrophysics observations.
    - Determine the utility of the Moon as a platform for observations of Earth.
    - Determine the utility of the Moon as a platform for observations of solar-terrestrial processes.

FINDINGS AND RECOMMENDATIONS

Lunar science has much broader implications than simply studying the Moon. There are strong linkages between the science goals recommended for the lunar exploration program and diverse scientific and applied concerns.

Principal Finding: Lunar activities apply to broad scientific and exploration concerns.

Finding 1: Enabling activities are critical in the near term.[1]

In order to take advantage of the information expected to be returned from missions flown before 2010 by the United States and other nations, the committee finds that enabling, preparatory activities will be critical in the near term.

> **Recommendation 1:** The committee urges NASA to make a strategic commitment to stimulate lunar research and engage the broad scientific community[2] by establishing two enabling programs, one for fundamental lunar research and one for lunar data analysis. Information from these two efforts, the Lunar Fundamental Research Program and the Lunar Data Analysis Program, will speed and revolutionize understanding of the Moon as the Vision for Space Exploration proceeds.

Finding 2: Explore the South Pole-Aitken basin.

As the oldest and largest basin in the solar system, the South Pole-Aitken Basin on the Moon is a unique location.

> **Recommendation 2:** NASA should develop plans and options to accomplish the scientific goals set out in the *New Frontiers in the Solar System: An Integrated Exploration Strategy*'s[3] high-priority recommendation, through single or multiple missions that increase understanding of the

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[1] The findings presented here are summarized from the more detailed findings given in Chapters 4 and 5.

[2] See National Research Council, *Issues Affecting the Future of the U.S. Space Science and Engineering Workforce: Interim Report*, The National Academies Press, Washington, D.C., 2006.

[3] See National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.

South Pole-Aitken basin and by extension all of the terrestrial planets in our solar system (including the timing and character of the early heavy bombardment).

Finding 3: Determine the composition and structure of the lunar interior.
Determination of the interior structure and composition of the Moon are high-priority scientific goals.

> **Recommendation 3:** Because a globally distributed network of many geophysical stations is critical for these investigations, an international effort should be pursued to coordinate the development of a standard, small set of key instruments (e.g., seismometer, thermal profiler, retro-reflector, etc.) and to cooperate in providing for its wide deployment across the Moon.

Finding 4: Maximize the diversity of lunar samples.
The Moon is a complex, heterogeneous body. Samples of the Moon from diverse sites are necessary to reach science goals.

> **Recommendation 4:** Landing sites should be selected that can fill in the gaps in diversity of lunar samples. To improve the probability of finding new, ejecta-derived diversity, every landed mission that will return to Earth should retrieve at a minimum two special samples: (a) a bulk undisturbed soil sample (200 g minimum) and (b) at least 1 kg of rock fragments 2 to 6 mm in diameter sieved from bulk soil. These samples would be in addition to those collected at specific high-priority sampling targets within the landing site.

Finding 5: Proceed with lunar surface mission development and the site selection process.
Plans to return to the Moon will involve the selection of surface exploration sites. Many of the science goals the committee set out depend critically on site selection.

> **Recommendation 5:** Development of a comprehensive process for lunar landing site selection that addresses the science goals of Table 1[4] should be started by a science definition team. The choice of specific sites should be permitted to evolve as understanding of lunar science progresses through the refinement of science goals and the analysis of existing and newly acquired data. Final selection should be done with full input of the science community in order to optimize science return while meeting engineering and safety constraints.

Finding 6: Understand the lunar polar deposits and environment.
Almost nothing is known about the sources of volatiles at the lunar poles and the processes operating on these volatiles. Lunar polar deposits and the lunar polar environment are probably fragile.

> **Recommendation 6:** NASA should carry out activities to understand the inventory, lateral distribution, composition (chemical, isotopic, mineralogic), physical state, and stratigraphy of the lunar polar deposits. This understanding will be gained through analyses of orbital data and in situ data from landed missions in the permanently shaded regions. In situ studies should occur early enough in the lunar program to prevent substantial change in the polar environment due to robotic and human activities.

Finding 7: Understand and characterize the lunar atmosphere.
The lunar atmosphere is tenuous and therefore fragile. Its pristine state is vulnerable to alteration from robotic and human activities.

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[4] See pages 23 and 24 of this interim report.

> **Recommendation 7:** To document the lunar atmosphere in its pristine state, early observational studies of the lunar atmosphere should be made, along with studies of the sources of the atmosphere and the processes responsible for its loss. These include a full compositional survey of all major and trace components of the lunar atmosphere down to a 1 percent mixing ratio, determination of the volatile transport to the poles, documentation of sunrise/sunset dynamics, determination of the variability of indigenous and exogenous sources, and determination of atmospheric loss rates by various processes.

Finding 8: Evaluate the Moon's potential as an observation platform.

The Moon may be a suitable site for various scientific observations of Earth, Sun-Earth connections, astronomy, and astrophysics.

> **Recommendation 8:** The committee recommends that a thorough study be done by NASA to evaluate the suitability of the Moon as an observational site for studies of Earth, Sun-Earth connections, astronomy, and astrophysics.

Finding 9: Establish strong ties with international programs.

The participation of other nations in lunar exploration is a fact. Coordinated and cooperative international activities would benefit all participants.

> **Recommendation 9:** NASA is encouraged to explicitly plan and carry out activities with the international community for scientific exploration of the Moon in a coordinated and cooperative manner. The committee endorses the concept of international activities as exemplified by the recent "Beijing Declaration" of the 8th International Conference on Exploration and Utilization of the Moon.

The committee also presents several related findings and recommendations intended to facilitate a balanced program to reach the scientific goals:

Finding 1R: Optimize the partnership between NASA's Exploration Systems Mission and Science Mission Directorates.

> **Recommendation 1R:** Prior Space Studies Board reports examined management approaches to the integration of human exploration and space science. They found that an optimum approach consisted of establishing a science management office within (today) the Exploration Systems Mission Directorate, reporting jointly to the Science Mission and Exploration Systems Mission Directorates. Such an office should be established as soon as possible to ensure the productive involvement of science planning and implementation ab initio.

Finding 2R: Identify and develop lunar-specific advanced technology and instrumentation.

> **Recommendation 2R:** NASA should create an advanced technology program to develop lunar-specific capabilities that are critical to successful implementation of the lunar science strategy outlined in Table 1. This program should tap the creativity of the engineering and science communities to address development of robotic and instrumentation capability to meet needs that at present are unmet.

Finding 3R: Plan curatorial and principal investigator facilities for new lunar samples.

> **Recommendation 3R:** NASA should evaluate the future needs of curatorial facilities for the collection of new lunar samples. The state and availability of instrumentation for both curation

and analyses should be assessed. Such a study should include representatives of the science community in detailed planning of an appropriate strategy.

Finding 4R: Optimize astronaut lunar field investigations—an integrated human/robotic approach.

Recommendation 4R: NASA should provide astronauts with the best possible technical systems for conducting science traverses and emplacing instruments. An integrated human/robotic program should be developed using robotic assistants and independent autonomous/teleoperated robotic systems. The capabilities of these systems should be designed in cooperation with the science community and operations planning teams that will design lunar surface operations. Extensive training and simulation should be initiated early to help devise optimum exploration strategies.

1
Introduction

WHY THE MOON?

We know more about many aspects of the Moon than we know about any world beyond our own, and yet we have barely begun to solve its countless mysteries. In the decades since the Apollo missions there has been a widespread misperception that the Moon has already told us all the important things it has to tell, that scientifically it is a "been there, done that" world. Nothing could be further from the truth.

The Moon is, above all, a witness to 4.5 billion years of solar system history, and it has recorded that history more completely and more clearly than any other planetary body. Nowhere else can we see back with such clarity to the time when Earth and the other terrestrial planets were formed.

Planetary scientists have long understood the Moon's unique significance as the starting point in the continuum of the evolution of rocky worlds. Many of the processes that have modified the terrestrial planets have been absent on the Moon. The lunar interior retains a record of the initial stages of planetary evolution. Its crust has never been altered by plate tectonics, which continually recycle Earth's crust, or by planetwide volcanism, which resurfaced Venus only half a billion years ago, or by the action of wind and water, which have transformed the surfaces of both Earth and Mars. The Moon today presents a record of geologic processes of early planetary evolution in the purest form. Its airless surface also provides a continuous record of solar-terrestrial processes.

For these reasons, the Moon is priceless to planetary scientists: It remains a cornerstone for deciphering the histories of those more complex worlds. But because of the limitations of current data, researchers cannot be sure that they have translated the message correctly. Now, thanks to the legacy of the Apollo program, it is possible to pose sophisticated questions that are more relevant and focused than those that could be asked more than three decades ago. Only by returning to the Moon to carry out new scientific explorations can we hope to close the gaps in our understanding and learn the secrets that the Moon alone has kept for eons.

INTERNATIONAL LUNAR EXPLORATION

The lunar exploration activities of the recent past and the near future are pervasively international in scope. The European Space Agency launched SMART-1 to the Moon in September 2003 on a technology-demonstration mission to validate solar-electric propulsion systems. After entering orbit around the Moon in November 2004, SMART-1 began limited studies of the lunar surface with a suite of small, innovative instruments. SMART-1 has scheduled an end-of-mission impact on the lunar nearside along with coordinated observations during fall 2006.

The Japanese Aerospace Exploration Agency has planned two missions for near-term implementation, Lunar A and SELENE. Lunar A is designed to study the lunar interior using seismometers and heat-flow probes deployed by penetrators, but technical difficulties during testing have put the mission on hold. On the other hand, SELENE is a mature orbiter prepared for launch in 2007 for a 1-year nominal mission. The goals of SELENE are to study lunar origin and evolution and to develop technology for future lunar exploration. It carries an array of modern remote sensing instruments for global assessment of surface morphology and composition. SELENE also carries two sub-satellites that will enable the gravitational field of the farside to be measured accurately.

The Chinese National Space Administration formally announced its Chang'e lunar program in March 2003. Chang'e 1, a lunar orbiter with a broad complement of modern instruments, is prepared for launch in fall 2007. Chang'e carries several remote sensing instruments to study surface topography and composition as well as the particle environment near the Moon. In addition, Chang'e carries a fourwavelength microwave sounder to probe the regolith structure. Future elements being planned for the Chang'e program include a lander/rover and a later sample-return mission.

The Indian Space Research Organization will launch its Chandrayaan-1 spacecraft in early 2008 on a 2-year orbital mission to perform simultaneous composition and terrain mapping using high-resolution remote sensing observations at visible, near-infrared, x-ray, and low-energy gamma-ray wavelengths. This spacecraft will carry two sophisticated instruments from the United States to characterize and map mineralogy using near-infrared spectroscopy and to map the shadowed polar regions by radar. In addition to the remote sensing instruments, the Chandrayaan-1 spacecraft will also carry an instrumented probe that will be released and targeted for a hard surface landing.

NASA's Lunar Reconnaissance Orbiter (LRO) is scheduled for launch in fall 2008. LRO's goals are to improve the lunar geodetic net, evaluate the polar areas, and study the lunar radiation environment. A secondary payload, LCROSS, launched with LRO will result in an impact into a polar region target with coordinated analysis.

All of these participants in lunar exploration have expressed their intention of releasing data returned in a compatible format that will allow fruitful comparisons. A variety of coordinated and cooperative international lunar analyses have been proposed.

2

Scientific Themes, Goals, and Questions

This chapter is a brief summary of the important scientific themes and goals that can and should be addressed during implementation of the initial phases of the Vision for Space Exploration, the Lunar Precursor and Robotic Program (LPRP), and the early phases of human activities. In this new age of exploration, the most scientifically compelling objectives include elucidating solar system bombardment history using the Moon as a unique, singularly important "Rosetta stone," understanding the origin and evolution of the Moon and rocky planets, evaluating the nature and stock of volatile elements and other potential resources on the Moon, and assessing the utility of the Moon as an observational platform. The science goals and themes in this report derive from these objectives, based on the current status of scientific knowledge, and a summary of implementation options presented for each. Many of the science themes use the Moon to understand our solar system, while others address understanding of the Moon itself; both are valuable pursuits. A common set of basic science goals is identified along with priorities for research associated with each theme. Several of these science goals and themes encompass broad and compelling science and require multiple approaches and integrated analysis. Others themes need further study to determine their full merit. All themes will be documented in greater detail in the committee's full report.

Theme 1: The bombardment history of the inner solar system is uniquely revealed on the Moon.

The heavily cratered surface of the Moon testifies to the importance of impact events in the evolution of terrestrial planets and satellites and the exceptional ability of the lunar surface to record them all. Lunar bombardment history is intimately and uniquely intertwined with Earth's, where the role of early intense impacts and possible periodicity in large impact events in the recent past on the atmosphere, environment, and early life underpin our understanding of habitability. The correlation between surface crater density and radiometric age discovered on the Moon serves as the basis for estimating surface ages on other solid bodies, particularly Mars. Significant uncertainties remain in our understanding of the lunar cratering record and our ability to extend it to other planets and other solar systems. Returning to the Moon provides an unparalleled opportunity to resolve some of the fundamental questions that relate to these goals.

Assess the early impact flux. The radiometric ages of impact melt lithologies in the returned sample collection have been used as an argument for a late cataclysm, that is, a spike in the cratering rate around 3.9 billion years ago, just about the time life on Earth was emerging. However, the geologic setting of the Apollo landing sites led to a selective sampling of material from Nectaris, Serenitatis, and Imbrium. With currently available data, it is impossible to decide whether a cataclysm occurred or whether the cratering rate smoothly declined with time since lunar origin. Determining the ages of impact-melt rocks from the South Pole-Aitken (SPA) basin (the stratigraphically oldest lunar basin) and major impact basins within SPA will go a long way toward resolving this issue. The precision required to accurately date these events requires isotopic analysis of well-chosen samples in terrestrial laboratories.

Assess the recent impact flux. Variability in the recent lunar and terrestrial impact flux may be related to singular solar system dynamic events, such as asteroid breakups, and may have significant effects such as impact-induced mass extinction on Earth (e.g., the Cretaceous/Tertiary (K/T) boundary and currently hotly debated Permian/Triassic (P/Tr) boundary events). On Earth, there is a greater relative number of younger craters, possibly suggesting a recent increase in projectile flux, but the diameters and especially the ages of most terrestrial craters are so poorly known that the terrestrial impact flux is uncertain. The Moon records the projectile flux in the Earth-Moon system over the past ~3.5 billion years, and researchers can use it to determine whether this flux has been approximately constant, or has exhibited shorter-term variations or periodicity, by determining crater densities on known young surfaces, such as crater ejecta deposits, and radiometric ages of lunar soil spherules.

Determine the exact ages of key craters. Impact basins and young craters serve as stratigraphic benchmarks for determining the relative age of lunar surfaces that have not been or cannot be directly accessed. There is still considerable debate about the ages of individual impact basins on the Moon. For example, the Orientale basin cannot be dated precisely because no samples in the current collection can unambiguously be attributed to the Orientale formation event. While radiometric ages of Apollo 12 samples suggest a narrowly constrained age of 800 million to 850 million years for Copernicus, crater counts on the ejecta blanket of Copernicus indicate a significantly older age of up to 1.5 billion years. Again, to accurately date these events requires analysis of carefully chosen samples in terrestrial laboratories.

Understand the limitations in extending the lunar flux curve to other planets. There are several outstanding issues that merit detailed further study in understanding the lunar flux curve and being able to use it to date other planetary surface features. Examples include the abundance of secondary impact craters and how they can be distinguished, potential latitudinal and hemispherical asymmetries in the number of formed impact craters, and the exact shape of the size-frequency distributions of solar system projectiles.

In summary, the overarching science requirement is to *characterize and date the impact flux (early and recent) of the inner solar system*.

Theme 2: The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated body.

The origin and evolution of the Moon. One of the key motivations for studying the Moon is to better understand the origin of the planets of the inner solar system in general, and that of Earth in particular. The origin of the Moon is inextricably linked to that of Earth. The precise mode of formation affected the early thermal state of both bodies and, therefore, affected the subsequent geologic evolution. The leading hypothesis at present is that the Moon formed as the result of the impact of a Mars-sized object with the growing Earth. However, the details of the process are not clear, and even its validity is not proven. Because the Moon's geologic engine largely shut down long ago, its deep interior is a vault containing a trove of information about its initial composition, differentiation, and crustal formation, and subsequent magmatic evolution. During and immediately after accretion, the Moon underwent primary differentiation involving the formation of a (presumably) iron-rich core, a silicate mantle, and a light, primordial crust. The initial bulk composition, as well as the pressure and temperature conditions during this separation, will be reflected in its current chemistry, structure, and dynamics. Although researchers have some information on the composition of the outermost layers of the Moon's crust, that of the bulk crust is less well known, and even its thickness is not well established. The composition of the mantle can only be vaguely estimated, and the presence of compositional stratification, bearing on the late stages of differentiation and the efficiency of subsequent convective mixing, cannot be confirmed or denied. Furthermore, the size and the composition (e.g., Fe vs. FeS, or even $FeTiO_3$) of its core are unknown, except for loose bounds on its diameter.

The value of new data. Data concerning interior structure and dynamics are difficult to obtain but are worth considerable effort to achieve. Direct samples of mantle rocks, from the deeply excavated South Pole-Aitken (SPA) basin or xenoliths, can provide a detailed glimpse into upper mantle composition. Geophysical measurements are the best, and in some cases the only, way to obtain information about the composition and structure of the deep lunar crust, mantle, and core. Researchers know from terrestrial experience that seismology is the most sensitive tool for determining internal structure. The waves produced by seismic events can provide essential information on crust and mantle structure and the size and nature of the core. These measurements can be augmented with analysis of rotational dynamics from precision tracking of surface reflectors. The flow of heat from the Moon's interior is a primary indicator of the global energy budget in terms of sources (e.g., radiogenic, accretional) and the mechanisms that control its release (convection, conduction, volcanism). Knowledge of the heat flow provides important constraints (through inferences about internal temperatures) on the rheology and dynamic behavior of deeper layers of the Moon, on both global and regional scales.

Thus, a variety of geophysical and compositional analyses of the Moon will enable researchers to *determine the internal structure and composition of a differentiated planetary body.*

Theme 3: The Moon's crust is much more complicated than are the mare and highlands.

Understanding of the formation of the lunar crust and mantle is framed by the lunar magma ocean hypothesis, whereby the Moon melted as it accreted and then followed a planetwide crystallization sequence, resulting in a floating feldspathic crust underlain by a dense, mafic mantle. The concept of a planetary magma ocean, though founded on lunar science, has become the one applied to the history of all the terrestrial planets.

Though the concept of the lunar magma ocean continues to serve us well, geophysical, remote sensing, and sample analyses reveal a lunar crust that varies both laterally and vertically in composition, age, and mode of emplacement. The traditional, dichotomous mare-highland classification developed from Apollo experience is inadequate in describing the structure and geologic evolution of the lunar crust.

From the global remote sensing coverage of the Clementine and Lunar Prospector missions of the 1990s and the study of lunar meteorites, researchers now know they have an incomplete sampling of the lunar crust, including unique materials of great interest to science and in situ resource utilization (e.g., high-Ti basalts, pyroclastic glass deposits). Understanding the composition and structure of the lunar crust underpins many other science goals but is also first-order lunar science. By integrating global remote sensing, detailed regional geology, and precise sample studies, researchers gain a predictive capability that allows them to make smarter choices about where to send future robotic and human missions.

Determine the variety and origin of rock types. Large lunar terrains have distinct geochemical characteristics inferred to be the result of asymmetry in the crystallizing lunar magma ocean or later large impact events. The Apollo and Luna samples came largely from a single, unique terrain (mare), and there are several other types of terrains yet to be fully characterized. Sample return from well-characterized sites representing new terrains allows high-precision laboratory analyses of petrology, composition, and radiometric ages and the ability to continue experiments for decades. Global compositional information from remote sensing extends the knowledge gained from samples collected from across the entire Moon.

Assess the vertical stratigraphy of the crust. Geophysical models of the lunar crust are highly dependent on assumptions about the type and distribution of materials across the crust and at depth. A regional, active seismic network can probe the depth of the megaregolith, which is potentially important in lunar base construction, and will determine whether a compositionally distinct lower crust exists. Samples from, and detailed geologic maps of, regions that have exhumed materials from depth provide further constraints, which in turn can highlight new areas of interest for future exploration.

Determine the composition of the lower crust and bulk Moon. Current understanding of the origin and early evolution of the Moon depends on its bulk composition, which is poorly constrained until researchers can determine the types and extent of lunar crustal rocks. The South Pole-Aitken basin may have excavated or melted the lower crust of the Moon or may possibly even provide a window to the lunar mantle. Lunar pyroclastic flows may bring deep-seated rocks to the surface. Returned samples from these types of sites will enable detailed petrologic and compositional analyses to determine the lower crustal composition, and by inference, the bulk Moon.

Thus, the Moon provides an exquisite opportunity to *determine the compositional diversity (lateral and vertical) of rocks formed in a differentiated planetary body.*

Theme 4: Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.

Volcanism is a well-documented and information-rich phase in the evolution of terrestrial planets. For the Moon, several key questions about its volcanic history have yet to be answered:

- *What are the origin and variability of basalts?* Many different types of mare basalts are represented in both the Apollo and Luna collections and in lunar meteorites, yet key basalt flows, identified from orbit, remain unsampled and their detailed chemistry and absolute ages are unknown.
- *How old is the youngest mare basalt?* Recent crater counts suggest that some of the basalts in Oceanus Procellarum might be as young as 1.2 billion years—an age unrepresented anywhere in the sample collection and an important calibration point for understanding lunar volcanism, thermal evolution, and the impact cratering flux.
- *What are the compositional range and extent of lunar pyroclastic deposits?* Pyroclastic volcanism offers the most direct sampling of the lunar mantle; within the existing sample collection, the range of composition is large, and it is likely that this range will grow even larger as researchers discover and sample new deposits.
- *What is the flux of lunar volcanism and how did it evolve through time?* The magma production rate through time is not known in detail, nor is the chemical evolution of these magmas and the thermal evolution of the Moon overall. The link between basalt composition and age requires better definition.

Understanding the history of the Moon and its thermal and magmatic evolution entails understanding the origin of the earliest crust, the thermal and dynamic evolution of the lunar mantle, how magma production rates changed with time, and the processes that formed highland igneous rocks—all of which can be addressed wholly or in part by answering the questions above. Namely, samples of basalts that erupted on the lunar farside will help elucidate at what depths melting occurred, when eruptions happened, and whether the composition of the mantle is uniform from the nearside to the farside. Samples of the youngest basalts will help constrain how basaltic processes have evolved over time. A range of subsurface sounding methods will permit determination of the thickness and structure of individual benchmark basalt flows. Investigating the thermal state and history of the interior (e.g., through careful measurements of the interior heat flow) will establish the thermal constraints on magma production through time.

Thus, the character of volcanism on the Moon allows us to *determine the time scales and compositional and physical diversity of volcanic processes.*

Theme 5: The Moon is an accessible laboratory for studying the impact process on planetary scales.

Impact cratering is a fundamental process that affects all planetary bodies. Understanding of cratering mechanics is heavily biased by observations of craters on Earth and in Earth-based laboratories. Though this understanding has been scaled as much as possible for lunar gravity, there are many untested hypotheses about lunar cratering, including the detailed structure and rim diameter of multi-ring impact basins, the effects of target composition on crater morphology, the amount of central uplift within craters, the existence and extent of impact melt sheet differentiation, the mixing of local and ejecta material, and scaling laws for oblique impacts. In this context, the Moon provides unique information because it allows the study of cratering processes over several orders of magnitudes, from micrometeorite impacts on glassy lunar samples to the largest basin in the solar system, the South Pole-Aitken basin. The large number of lunar impact craters over a wide range in diameters provides the basis of statistically sound investigations, such as, for example, depth/diameter ratios, which in turn have implications for the possible layering and strength of the lunar crust but can also be extrapolated to other planetary bodies. Thus, the Moon is a valuable, easily accessible, and unique test bed for studying impact processes throughout the solar system.

The decadal survey report *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NRC, 2003) asked, "How do the processes that shape the contemporary character of planetary bodies operate and interact?" Cratering is one of several such processes, affecting the lunar surface, the crust, and possibly even the mantle; each advance in understanding of cratering mechanics moves researchers closer to answering that key scientific question.

Current hypotheses and assumptions about cratering processes underpin many of the hypotheses about the composition and evolution of the lunar crust, and thus the rest of the solar system. For example, answering the question of whether or not impact melt sheets can differentiate will either open or close a door on the range of potential origins of igneous rocks found on the Moon. Some cratering hypotheses are rarely questioned and have become sufficiently accepted that they are now "rules of thumb." An example of this involves the amount of central uplift within craters. Models of crustal structure and character have been derived from data on the composition of central peaks of lunar craters; if these peaks did not originate from the depths currently assumed, then these models might require re-evaluation. Thus testing and validating both the wildest and the most accepted hypotheses about the cratering process are critical to being able to correctly interpret lunar geology, and ultimately that of the solar system.

To achieve this, sample return from craters and basins, including a vertical sample of a basin melt sheet, is needed. In addition, the walls, rim, and central peaks of compositionally diverse major complex craters need to be mapped in geologic detail, beginning with orbital measurements and followed by selected field studies of at least one crater. The structure of large multi-ring basins needs to be mapped through drilling programs or geophysical measurements.

In summary, implementation of the Vision for Space Exploration presents an opportunity to *characterize the cratering processes on a scale relevant to planets.*

Theme 6: The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.

Regoliths, exemplified by the lunar regolith, form on airless bodies of sufficient size to retain a significant fraction of the ejecta from impact events. The regolith contains representative rocks from both local and distant sources, the alteration products induced by meteoroid and micrometeoroid impacts, and modifications due to the implantation of solar and interstellar charged particles, radiation damage, spallation, exposure to ultraviolet radiation, and so on. Knowledge of the processes that create and modify the lunar regolith is essential to understanding the compositional and structural attributes of other airless planet and asteroid regoliths in general. Because the regolith collects the products of the interaction of impactors and radiation with the surface, the composition of ancient regoliths, protected by overlying layers of volcanic materials, may yield information on the time-history of the Sun and interstellar particle fluxes in the inner solar system. Understanding the "space weathering" processes that affect the regolith, particularly the distribution of materials volatilized by impacts, is essential to the interpretation of spectral data used to map the distribution of rock types on the surface. Because the effects of space weathering depend on both the composition and the exposure history of the surface, new samples that represent materials of different initial composition and age should be prime candidates for study.

Layers of interspersed volcanic rocks and ancient regolith can be observed or inferred in the maria, where the periods between successive volcanic flows were periods of new regolith formation. Sampling of these ancient regolith layers can be carried out by drilling through the rock column or by collecting rocks in the walls of impact craters or along rilles. If these ancient regolith layers have been indurated through the thermal effects of the overlying lavas, they might also be discovered in the rock fragments that surround impact craters. Samples may be available at many mare locations, but targeted collection would benefit from on-site human field observations to identify and retrieve the desired sample materials. For example, a sampling device (e.g., a rover) could sample the stratigraphic column in an impact crater wall or in a rille, with an astronaut making critical observations of the properties of the layered sequence using handheld sensors.

The regolith within permanently shadowed regions may have special properties, such as cementation, extreme brittleness, or grain size effects, especially if the suspected volatile deposits, such as water ice, have interacted with the material. The chemical, mineralogical, and physical properties of these deposits could be representative of similar deposits on Mercury or elsewhere in the solar system.

Most lunar resources will be derived from the regolith. Understanding the mineralogy, volatile concentrations, and physical properties of the regolith and having a better understanding of regolith formation and history will be crucial to exploring for and developing extractive techniques for regolith-based resources. This is particularly true for the polar regions, for which there is no current basis for understanding these properties in detail.

Physical properties and many volatile concentrations can be best studied through in situ surface investigations. The details of chemical weathering and charged particle interactions require the collection of samples for study in terrestrial laboratories. The collection of samples of ancient regolith requires field observations carried out by astronauts.

In summary, multiple opportunities will be present during implementation of the Vision for Space Exploration to *constrain processes involved in regolith evolution and decipher ancient lunar environments from regolith samples.*

Theme 7: The Moon may provide important information about the early Earth and the origin of life.

Using the Moon to study Earth's history. Studying Earth's biologic history is a major topic for NASA and for astrobiology. To understand how life may have originated requires an understanding of Earth's distant past and its relationship to the history of the Sun and of the cosmic-ray and cosmic-dust environment. These topics are a portion of the goals of NASA's Astrobiology Roadmap, namely to understand how life emerges from cosmic and planetary precursors, and to understand how past life on Earth interacted with its changing planetary and solar system environment.

Studies of four key eras are of import:

1. The characteristics and environment of Earth at the time when life originated, a period currently believed to have spanned the time from 4.2 billion to 4.4 billion years ago.
2. The period when the Late Heavy Bombardment (LHB) may have occurred, around 3.9 billion years ago. There are suggestions that during this period the number of different forms of life was reduced sharply going through a bottleneck where only organisms that thrived at high temperatures survived.
3. The period from 2.1 to 2.9 billion years ago, when oxygenic photosynthesis developed and when snowball-Earth and hothouse-Earth sequences are proposed to have occurred.
4. Late Proterozoic, the period from 0.55 billion years ago to 1.2 billion years ago, the era in which multicellular eucaryotes came to prominence. It was also the period when a hypothesized "snowball Earth" may have occurred and a period in which the oxygen abundance in Earth's atmosphere increased dramatically.

For these eras, terrestrial analyses of zircons are starting to give clues to the thermal and aqueous history of early Earth. But information on solar variations, cosmic dust input, or unmetamorphosed samples of the early Earth surface are not currently available from Earth. There is high interest in comparing the lunar bombardment history with Earth's geologic record. This connection can be explored by studying the lunar cratering rate (as discussed in Theme 1). There is interest in studying cosmic dust infall rate changes and solar activity changes that can be related to terrestrial events. Fragments of early Earth might also have been transported to the Moon during the LHB. Study of ancient lunar regolith (discussed above in this report) can provide information in each of these areas of interest. However, the search for pieces of early Earth will involve looking for a minute and unusual fraction of the regolith material and should logically be deferred until in situ resource utilization (ISRU), which will require large amounts of lunar regolith material for processing, is implemented.

Significant opportunities exist, interwoven with other themes, to *utilize lunar observations to characterize Earth's history.*

Theme 8: The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history.

The lunar polar environment and its importance. The Moon and Mercury share a microenvironment at their poles that is unique in the solar system. The very small obliquity of these small planets causes topographic depressions near the poles to be permanently shaded from sunlight, allowing them to achieve extremely low temperatures ranging between 50 and 80 K; these temperatures are not expected elsewhere in the solar system within the orbit of Neptune and nowhere else on exposed silicate surfaces. The presence of these cold surfaces adjacent to the hot surfaces of the Moon and Mercury may allow cold trapping of volatile material that has impacted or otherwise been introduced to the surfaces of these objects. Any water or other volatile molecule that encounters a cold trap surface will be permanently trapped with respect to sublimation, depending on the temperature of the trap and the vapor pressure of the species. The trapping process suggests that the lunar (and Mercurian) poles may record a history of volatile flux through the inner solar system over the lifetime of the traps. The importance of these regions for understanding solar system volatile materials is analogous to the importance of meteorites in Antarctica as a valuable resource for studying solar system refractory materials. The committee also notes that the polar regions may provide critical resources, such as high concentrations of hydrogen and possibly water for future exploration. By answering the science issues described here, important information will be provided for potential ISRU opportunities.

Scientific questions about the polar environment. The most important scientific questions deal with determining the compositional form of the polar volatiles, their sources, their alteration during transport and sequestration, and the nature of any processes that may have altered them in situ. The potential sources are solar wind gas, volatile-rich comets, asteroids, and interplanetary dust particles, and even volatile material from giant molecular clouds through which the solar system periodically passes. The possible processes operating on these volatiles range from mass fractionation during transport, to retention from burial and chemical alteration processes, to losses from solar wind and galactic ultraviolet radiation and micrometeorites. Studies of transport and alteration processes are also needed for understanding how robotic and human missions to the Moon can affect the pristine lunar polar environment.

Current knowledge and future opportunities. The complexity of the lunar polar environment is matched by a near-total lack of data to constrain understanding. Radar results for Mercury and additional neutron data for the Moon have achieved the zero-order existence proof that cold trapping of volatiles does occur, but the chemical identity of the polar materials, their sources and evolution, and the explanation for the differences between Mercury and the Moon are entirely unknown. Without new data, the value of the polar deposits for addressing larger issues in planetary science is unknown.

Analysis of existing orbital data (Clementine, Lunar Prospector) and data from planned orbital missions will contribute significantly to understanding of the lunar polar volatile deposits. For example, the Lunar Reconnaissance Orbiter (LRO) will provide photometry, morphology, topography, and temperature information that will improve knowledge of the polar environment. LRO will also provide information about the hydrogen distribution near the poles and possible surface frosts if they are present. The M3 infrared spectroradiometer on Chandryaan-1 could potentially detect water or hydroxyl features through measurement of surfaces illuminated by sunlight scattered by nearby topographic highs. Future measurements that make high-spatial-resolution volatile measurements (<10 km) at latitudes down to 70° (the lowest latitude where most permanently shaded regions are expected) would be valuable to characterize the location and total inventory of the volatile deposits.

Even so, a positive result by upcoming orbital remote sensing missions will not answer the most compelling scientific questions; these can only begin to be addressed by robotic in situ measurements. (A negative orbital result does not diminish the potential scientific value of the poles, but does complicate their further investigation if candidate landing sites are not identified.)

First, the localized existence and lateral distribution of volatile deposits within permanently shaded regions needs to be determined, since there are indications that these regions may be patchy within the shaded regions.

Second, when such deposits are found, the key measurements to answer the major science questions are measurements of elemental and isotopic composition, and physical and mineralogical characteristics of the volatile deposits. These measurements may need to be made as a function of stratigraphy since there are indications that these deposits are layered.

In addition, by making these measurements, more information will be gained about the physical properties of the regolith in permanently shaded regions for which there is almost no known information.

The results of these initial measurements would guide further investigations. If it can be shown that polar cold traps preserve volatiles with high fidelity, such that source characteristics can be inferred or in contrast reveal significant degrees of processing (e.g., to complex organics), subsequent more detailed analysis is warranted, likely using cryogenically preserved returned samples.

In summary, a unique opportunity exists to *characterize the volatile compounds of polar regions on an airless body and determine their importance for the history of volatiles in the solar system.*

Theme 9: Further exploration can vastly improve understanding of the fragile lunar atmosphere.

The lunar atmosphere is the nearest example of a surface boundary exosphere (SBE)—the most common type of satellite atmosphere in the solar system. SBEs are tenuous atmospheres whose exobase is at the planetary surface. Because the individual atoms and molecules rarely collide in SBEs, kinetic chemistry is all but nonexistent, but important structural, space physics, and dynamical issues can be studied. The lunar atmosphere is the only SBE atmosphere in the solar system that is sufficiently accessible that researchers can expect to study it in detail.

SBE atmospheres are known to exist on Mercury, Europa, Ganymede, Callisto, and Enceladus; they are expected to exist on many other satellites and perhaps even Kuiper Belt objects. They are the least studied and least understood type of atmosphere in the solar system. They offer to teach us new insights into surface sputtering, meteoritic vaporization processes, exospheric transport processes, and gas-surface thermal and chemical equilibration. The lunar atmosphere is the only SBE atmosphere in the solar system that is sufficiently accessible that researchers can expect to study it in detail using both landed and orbital techniques.

The lunar atmosphere was long speculated about, but the first detection of species came from the Apollo Lunar Surface Experiments Package (ALSEP) and the scientific instrument module (SIM) instruments in the orbiting Apollo Service Module bay. Among the species discovered by Apollo missions were Ar, Po, Pb, Ra, and Rn, all of which emanate from the lunar interior via outgassing. As such, the lunar atmosphere represents a window into the workings and evolution of the lunar interior.

After Apollo, ground-based observers detected the alkali tracer species Na and K, which are also present in the SBE atmospheres of Mercury, Io, and other Galilean satellites, thereby strengthening the utility of lunar SBE studies for enhancing knowledge of similar atmospheres across the solar system.

Evidence for volatile species, including H_2O, CO, CO_2, and CH_4, was also detected sporadically by Apollo sensors, but these detections remain unconfirmed. The detection and study of volatiles are of great scientific interest and have obvious implications related to the trapping of ices that could represent resources to be exploited at the lunar poles.

Apollo ALSEP surface station instruments revealed that the mass of the native lunar atmosphere is on the order of 100 tons (3×10^{30} atoms, equivalent to $\sim 10^{11}$ cm^3 of terrestrial air at sea level [i.e., a cube of terrestrial air roughly 50 × 50 × 50 cubic meters at standard temperature and pressure]). Yet ALSEP total lunar atmosphere mass measurements failed to identify a census of species that comes anywhere close to the total mass of the lunar atmosphere: in fact, over 90 percent of the molecules in the Moon's atmosphere are currently compositionally unidentified.

As a result of its low mass, the lunar atmosphere is incredibly fragile. A typical lunar surface access module (LSAM) landing will inject some 10 to 20 tons of non-native gas into the atmosphere, severely perturbing it. A human outpost might see sufficient traffic and outgassing from landings, lift-offs, and extravehicular activities (EVAs), for example, to completely transform the nature of this pristine environment. *As a result, the committee recommends a strong early emphasis on studies of the native lunar atmosphere.*

The key scientific questions to address are the following: What is the composition of the lunar atmosphere? How does it vary in time with impacts, diurnal cycles, solar activity, and so on? What are the relative sizes of the sources that create this atmosphere and the sinks (loss processes) that attack it?

Early observational studies to address these issues and the concern over human-induced modification of the ancient, native environment should include:

- A complete census and time variability of the composition of the lunar atmosphere;
- Determination of the average rate of volatile transport to the poles;
- Documentation of sunrise/sunset dynamics;
- Determination of the time variability of indigenous (e.g., outgassing, sputtering) and exogenous (e.g., meteorite and solar wind) sources; and
- Determination of typical loss rates by various processes (e.g., photoionization, surface chemistry, Jeans escape, Michael-Manka mechanism).

Such studies could be completed from early surface networks, fixed or mobile landers, or orbiters, or a combination of any two with experiments that would include ion-mass spectrometers, optical/ultraviolet spectrometers, and cold cathode gauges.

Later, as rocket traffic and human activities perturb the lunar atmosphere from its native state, studies of the environmental effects of human and robotic activity would be highly illuminating, as an "active experiment" in planetary-scale atmospheric modification.

Before extensive human and robotic activity alters the tenuous lunar environment, it is important to *understand processes involved with the atmosphere (exosphere) of airless bodies in the inner solar system.*

Theme 10: The Moon may provide an excellent platform for specific types of observations.

The Moon is a platform that can potentially be used to make observations of Earth (Earth science), the interaction of the solar wind with the magnetosphere (viz, the solar-terrestrial connection), and the rest of the universe (astrophysics and astrobiology). The Moon provides both advantages and disadvantages for such observations. The optimum development of science first requires understanding the potential benefits and limitations of using the Moon as an astronomical or Earth-observing site.

The committee is in the process of studying the benefits and limitations of utilizing the Moon as an observational platform, referring to pertinent NRC studies (especially *Priorities in Space Science Enabled by Nuclear Power and Propulsion*, The National Academies Press, Washington, D.C., 2006). The full report will present these considerations.

Overall, in the near future, it is important to *determine the utility of the Moon for astrophysics observations and as a platform for making observations of Earth and of solar-terrestrial processes.*

3
Related Themes and Goals

The committee also identified several related themes and goals that are needed for implementation of the science themes and goals.

Theme 1R: Optimizing the Collaboration Between Science and Human Exploration

Successful implementation of science in a program of human exploration is highly dependent on a cooperative relationship between the two communities. To acquire lessons learned from past experience, the SSB Committee on the Human Exploration of Space (CHEX) conducted a study of science prerequisites, science opportunities, and science management in the human exploration of space.[1] For science management, CHEX looked at the Apollo, Skylab, Apollo-Soyuz, and Shuttle/Spacelab programs to determine what organizational relationships, roles, and responsibilities contributed to superior outcomes.

CHEX found that human exploration offers a unique opportunity for science accomplishment and as such should be viewed as part and parcel of an integrated human exploration-science program. CHEX developed three broad management principles, which, if implemented, would improve the probability of a successful synergy between science and human exploration:

1. *Integrated Science Program*—The scientific study of specific planetary bodies, such as the Moon and Mars, should be treated as an integral part of an overall solar system science program and not separated out simply because there may be concurrent interest in human exploration of those bodies. Thus, there should be a single NASA headquarters office responsible for conducting the scientific aspects of solar system exploration.
2. *Clear Program Goals and Priorities*—A program of human spaceflight will have political, engineering, and technological goals in addition to its scientific goals. To avoid confusion and misunderstandings, the objectives of each individual component project or mission that integrates space science and human spaceflight should be clearly specified and prioritized.[2]
3. *Joint Spaceflight/Science Program Office*—The offices responsible for human spaceflight and space science should jointly establish and staff a program office to collaboratively implement the scientific component of human exploration. As a model, that office should have responsibilities, functions, and reporting relationships similar to those that supported science in the Apollo, Skylab, and Apollo-Soyuz Test Project (ASTP) missions.

Consistent with the principles enunciated above, CHEX found a definitive correlation between successful science accomplishment and organizational roles and responsibilities. In particular, the quality of science was enhanced when the science office (SMD now) controlled the process of establishing science priorities, competitively selecting the science and participating scientists and ensuring proper attention to the end-to-end cycle ending in data analysis and publication of results.

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[1] *Scientific Prerequisites for the Human Exploration of Space*, 1993; *Scientific Opportunities in the Human Exploration of Space*, 1994; and *Scientific Management in the Human Exploration of Space*, 1997 (National Academy Press, Washington, D.C.).

[2] See especially pages 2-3 in the section “The Role of Science” in the 1993 report *Scientific Prerequisites for the Human Exploration of Space*, pages 6-7 in the 1994 report *Scientific Opportunities in the Human Exploration of Space*, and pages 17-29 in Chapter 3, “Science Enabled by Human Exploration,” of the 1994 report.

Theme 2R: Identification and Development of Advanced Technology and Instrumentation

Robotic technology. The combination of surface mobility and manipulation is a key requirement for extracting science on the lunar surface, both during precursor and sortie missions. For autonomous/semi-autonomous robotic operations on the lunar surface, gaps exist in current robotic capabilities and should be addressed in order to enable achievement of science goals. These challenges include development of the following capabilities:

- Long-distance navigation and access:
  - Command of a single vehicle to access and maneuver on all lunar terrain types, such as disturbed lunar soil, steep rim slopes, and craters and basins; cover long distances; and carry/deploy a payload.
  - Robust operation for extended periods of time, including functioning during the 14-day lunar night.
  - Navigation in shadowed regions, such as those found in the polar craters.
  - Visualization of the environment for human supervision/telepresence.
- Instrument placement and manipulation:
  - Dexterous placement of a science instrument precisely on a designated target with a required contact force, while accounting for lunar gravity and environmental constraints.
  - Interchange of end-effectors needed to achieve contact measurements.
  - Robust acquisition and manipulation of multiple science samples and transport to a location of interest.
  - Manipulation of sensors for active experimentation, such as drilling and placement of instruments beneath the lunar surface.

Instrumentation. Some types of in situ and laboratory measurement technology have not yet achieved their potential to accomplish scientific goals. For use on both robotic and human missions and for returned samples, development of the following instrumentation capabilities poses a challenge:

- In situ determination of the radiometric age of a crystalline igneous or impact melt with a precision of 10 percent or better of the age, which would address fundamental issues in lunar and planetary geochronology without sample return, preserving return mass for more sophisticated analysis.
- In situ measurement of cosmic ray exposure ages, which is essential to establish more recent dates.
- In situ routine microanalysis (major elements, mineralogy) and imaging at the 10-micron scale, for fields of view of a few millimeters.
- In situ measurement of minor and trace elements for gram-sized samples.
- High-resolution remote sensing, at the scale of tens of centimeters, to allow precise targeting of some types of samples, and to inform the crews and ground support of the types and distributions of materials present at the site.
- Upgrading of analytical instrumentation for sample analyses in the curatorial facilities and in principal investigators' laboratories.

Capability is also needed for rapid-analysis contact analytical tools to facilitate decision making during human and robotic geologic or geophysical traverses. Hard landers, such as penetrators that emplace instruments, will require shock-hardened variants of the above and other instruments.

Theme 3R: Lunar Surface Mission Development

Apollo experience demonstrated both the complexity of planning lunar surface operations and the benefits of doing so. The planning started long before flights and included determination of science objectives, landing site selection, astronaut science training, science team selection, traverse planning, sampling strategies, geophysical station development (ALSEPs), full-up mission simulations, and data analysis preparations.

A similar range of preparation will be essential for implementation of the Vision for Space Exploration. Much of what was learned by hard experience on Apollo can be efficiently incorporated into future planning. Obviously a lot of the detail will have to, and should, await a date closer to mission implementation; however, certain aspects can be initiated now with relatively low investment. These include considering:

1. Sites on the Moon that would prove most productive for scientific investigation;
2. The type of missions—sortie and/or outpost—that can best satisfy high priority science objectives;
3. The range of crew mobility needed; and
4. The optimum mix of robotics and human activity that best meets the science objectives, taking into consideration operational constraints (this should consider pre-human robotic missions).

Two areas are of special interest for early study:

1. Landing site selection. NASA's plans to return to the Moon necessarily involve the selection of surface exploration sites. Such sites will be selected based on a number of factors. Safety will undoubtedly be a prime consideration, but today's technology and capability basically open up the entire Moon to exploration. Where one explores then becomes a matter of which sites best provide the venues for accomplishing exploration goals. These will include science, ease of access, build-up of an outpost or base, potential for development of in situ resource utilization (ISRU), commercial potential, and so on. Many of the science goals elucidated in this interim report depend critically for their successful accomplishment on getting to specific lunar landing sites. Undoubtedly a given site might satisfy many of the requirements of the different goals. And, in fact, site selection might have to satisfy a fundamental requirement to maximize meeting multiple requirements.

The identification of specific candidate landing sites requires more time than was available for this interim report.

2. Surface mission operational planning. Apollo experience demonstrated that the most valuable resource on the Moon is time. There is inevitably more to be done than time allows. For example, astronauts were constantly under pressure to "move on to the next station." Many opportunities to examine discoveries in more detail were missed (e.g., orange soil on Apollo 17, "genesis" rock on Apollo 15). Things that went wrong took time away from meeting the timelines (e.g., a stuck drill). It is necessary to devise methods to conserve astronaut time, doing robotically those things that do not take greatest advantage of the human capability to observe, make decisions, and use manual dexterity to advantage. NASA should undertake an examination of Apollo missions with an eye toward identifying time-saving opportunities.

The typical Apollo-type sortie mission of 2 to 3 days is too short to accomplish the level of scientific investigation now merited by our improved understanding of lunar science. If, however, sortie missions are a selected mode for early Vision missions (currently, sorties up to 7 days are under consideration), then planning is needed to increase their efficiency. A possible mode is to precede the human flight with robotic rover precursors in which the rover, similar to the Mars Exploration Rover (MER) on Mars, conducts reconnaissance and identifies high-priority traverse locations for astronaut investigation. The rovers on Apollo missions 15 to 17 demonstrated the benefit of mobility; their use was limited primarily by safety and life-support supply considerations. Analysis of the extent to which such constraints can be relieved on future missions is necessary. Similarly, telerobotic operations during a human mission might add immeasurably to mission efficiency.

The attributes of the lunar outpost concept for purposes of scientific investigation deserve study. The potential advantages are increased time for detailed geologic study, geophysical instrument emplacements and traverse surveys, preliminary sample selection, follow-up on results obtained on earlier flights to the outpost, and utilization of logistics previously emplaced. An outpost would warrant a greater investment in terms of reusable resources, for example, a multi-mission rover with resuppliable on-board life support and sophisticated analytical instrumentation. Such a rover could be used in automated mode between outpost visits. Many of these attributes were being considered in the 1960s as follow-ons to the initial Apollo missions but were, obviously, never executed when missions after Apollo 17 were canceled.

4
Priorities, Primary Scientific Findings, and Recommendations

Table 1 provides a summary of scientific objectives for early lunar exploration and their principal implementation modes. These objectives and implementations provide a rich basis for the extraction of specific objectives that could be organized into a science program. The committee provides the following prioritization of these lunar science goals that flow from the 10 themes discussed in Chapter 1 and that can be accomplished by lunar measurements and analyses. The committee has used the prioritization criteria adopted by the decadal survey *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NRC, 2003) as a guideline: scientific merit, opportunity, and technological readiness.

1. Fundamental Solar System Science
    - Characterize and date the impact flux (early and recent) of the inner solar system.
    - Determine the internal structure and composition of a differentiated planetary body.
    - Determine the compositional diversity (lateral and vertical) of the ancient crust formed by a differentiated planetary body.
    - Characterize the volatile compounds of polar regions on an airless body and determine their importance for the history of volatiles in the solar system.

2. Planetary Processes
    - Determine the time scales and compositional and physical diversity of volcanic processes.
    - Characterize the cratering process on a scale relevant to planets.
    - Constrain processes involved in regolith evolution and decipher ancient environments from regolith samples.
    - Understand processes involved with the atmosphere (exosphere) of airless bodies in the inner solar system.

3. Other Opportunities (additional information is required for these)
    - Utilize data from the Moon to characterize Earth's early history.
    - Determine the utility of the Moon for astrophysics observations.
    - Determine the utility of the Moon as a platform for observations of Earth.
    - Determine the utility of the Moon as a platform for observations of solar-terrestrial processes.

Several fundamental solar system science issues are given higher priority because of their broad importance to understanding the way in which the Moon and planets have evolved as solar system bodies, especially in the first 500 million years of solar system evolution. These goals are readily addressed in the time frame specified by this report. Although still fundamental and having implications for the same processes on other planets, several other planetary processes are given somewhat lower priority because they are (1) more highly linked to later Vision activities or events and (2) focus on the Moon as a specific body. A few, such as cratering processes and ancient regolith sampling, appear to require components that extend considerably into the period when human involvement is significant. Other opportunities are listed as lower priority at this time primarily due to the lack of input to the committee for assessing these opportunities.

The committee will provide a more complete prioritization of, and increased specificity for, these opportunities in its full report if relevant information becomes available.

TABLE 1 Science Themes, Goals, and Implementation

	Implementation				
Science Themes The scientific goals for each theme are discussed in detail in the text.	**a. Information Extraction** An enabling new framework for lunar exploration will be provided by data from SMART-1, SELENE, Chang'e, Chandrayaan-1, and LRO. The assumption is that all missions and key instruments will be successful.	**b. Orbital Measurements** Orbital measurements not included in the complement of missions planned for launch by 2008. The assumption is that the four missions planned will return appropriate data as planned; if not, new measurements that provide similar high-priority compositional and geophysical data need to be acquired.	**c. Sample Return** The types of returned samples and of science analyses required are identified.	**d. Landed Experiments, Instruments, and Rovers** These include science measurements for/from landed sites; category also encompasses penetrators/impactors.	**e. Human Fieldwork** Science areas that specifically benefit from human capabilities are identified.
1. The bombardment history of the inner solar system is uniquely revealed on the Moon.	Crater counts of benchmark terrain using high-resolution images.	Targeted higher-resolution images of specific terrains.	Sample return from the impact melt sheet of SPA, from young basalt flows, and from benchmark craters (e.g., Copernicus and Tycho).	Development of in situ instrumentation for dating.	Field observations provide critical geologic context; human interaction improves chances of obtaining best/most appropriate samples.
2. The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated body.	Farside gravity. High-quality topographic information. Possible information on heat flow and magnetic sounding results.	Relay orbiter for farside stations (e.g., seismic).	Samples from the interior are important constraints on lunar geochemistry and geophysics (e.g., remanent magnetism).	Simultaneous, globally distributed seismic and heat flow network. Expanded retroreflector network.	Although some landed experiments can be emplaced autonomously, it is assumed that more capable sensors are possible with human guidance/assistance.
3. The Moon's crust is much more complicated than are the mare and highlands.	Detailed global elemental and mineralogical information in a spatial context. Search for and documentation of a diversity of rock types using returned samples and lunar meteorites.	Higher-spatial-resolution compositional data are desirable from priority targets. Relay orbiter for farside stations (e.g., seismic).	Return samples from priority targets. Every return mission should include a bulk soil and a sieved sample with geologic documentation.	Strategic site selection. Conduct in situ analyses and mineralogical and elemental characterization of the rocks and provide a thorough description of the geologic context. Determine the vertical structure using an active regional seismic network.	Field observations provide critical geologic context; human interaction improves chances of obtaining best/most appropriate samples.
4. Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.	Detailed global elemental and mineralogical information in a spatial context. Improved age-dating for basalts through crater counting.	Stratigraphy of specific basalt flows (subsurface sounding). High-spatial-resolution compositional data desirable.	Sample the youngest basalt flows. Need samples from unsampled benchmark lava flows and pyroclastic deposits. Sample a complete sequence of flows to determine the evolution of basalt composition.	Strategic site selection. Conduct in situ analyses and mineralogical and elemental characterization of the rocks and provide a thorough description of the geologic context.	Strategic site selection, core drilling, and active subsurface sounding to determine layering and volume.

continues

TABLE 1 *continued*

	Implementation				
Science Themes The scientific goals for each theme are discussed in detail in the text.	**a. Information Extraction** An enabling new framework for lunar exploration will be provided by data from SMART-1, SELENE, Chang'e, Chandrayaan-1, and LRO. The assumption is that all missions and key instruments will be successful.	**b. Orbital Measurements** Orbital measurements not included in the complement of missions planned for launch by 2008. The assumption is that the four missions planned will return appropriate data as planned; if not, new measurements that provide similar high-priority compositional and geophysical data need to be acquired.	**c. Sample Return** The types of returned samples and of science analyses required are identified.	**d. Landed Experiments, Instruments, and Rovers** These include science measurements for/from landed sites; category also encompasses penetrators/impactors.	**e. Human Fieldwork** Science areas that specifically benefit from human capabilities are identified.
5. The Moon is an accessible laboratory for studying the impact process on planetary scales.	Detailed geologic mapping of compositionally diverse craters and basins.	Evaluation of upper-surface stratigraphy (sounding). Determination of the shape of craters and the distribution of ejecta.	Sample returns from benchmark craters and basins.	In situ compositional and structural analyses of craters and basins (via traverses).	Core samples from impact melt sheets. Traverses across ejecta blankets.
6. The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.	Maps of regolith maturity and derivation of the temporal progression of space weathering. Identification of regions that contain ancient regolith.	Evaluation of upper-surface stratigraphy (sounding).	Regolith from unsampled terrain of diverse composition and age. Understand the evolution of the regolith. Sample old regolith where it is stratigraphically preserved.		Obtain paleoregolith samples (exposed in selected outcrops or through deep drilling).
7. The Moon may provide important information about the early Earth and the origin of life.	Cratering flux, regoliths.	Better understanding of lunar cratering flux through targeted high-resolution imaging to help establish history of impacts on early Earth.	Age dating of specific lunar craters and basins to improve understanding of impact history.		Obtain paleoregolith samples to determine early solar activity and cosmic dust flux, and their effects on early Earth.
8. The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history.	Primary understanding of polar environment (photometry, morphology, topography, temperature, and distribution and inventory of volatiles).	High-spatial-resolution distribution of volatiles on and in the regolith poleward of 70 degrees.	Cryogenically preserved sample return to determine the complexity of the polar deposits.	Understand physical properties of polar regolith. Determine the localized character and lateral and vertical distribution of polar deposits. Measure chemical and isotopic composition, and physical and mineralogical characteristics.	
9. Further exploration can vastly improve understanding of the fragile lunar atmosphere.		Variation in mass with time and compositional inventory ("with time" refers to the lunar diurnal and Earth-orbital/solar cycles).		Variation of mass with time and identification of dominant species. Environmental monitoring near human activity.	
10. The Moon may provide an excellent platform for specific types of observations.	Awaiting Further Input				

Many science objectives will require investigation by several techniques—orbital observations, in situ analysis, astronaut field observations, and analysis of returned samples—so a simple prioritization of individual objectives alone is not feasible. The committee has assumed that an "opportunity" criterion is specified by its statement of task, which directed it to consider LPRP robotic precursor missions and early human "sortie" missions similar to Apollo capabilities. These provide constraints of mass, power, and technology development on what can reasonably be available for implementation. "Technology readiness" is ambiguous for the more distant exploration schedule, which may allow many capabilities, currently unavailable, to be developed by the time of the missions. Nevertheless, some capabilities, such as deep drilling, are probably beyond the time horizon addressed in this report, and the committee has tried to accommodate this perspective. Although its task focused on science objectives and mission capabilities, the committee thought it necessary to consider the degree of preparation required for conducting the science that would be accomplished by the Vision.

With this introduction and the above discussion of science themes and priorities, the committee provides the following list of findings and recommendations, divided into two categories. The first category directly addresses the scientific objectives. In Chapter 5, related findings and recommendations are derived from the committee's consideration of the challenges facing NASA in the implementation of a lunar science program of the type envisioned by the science objectives and implementation approach recommended here.

PRINCIPAL FINDING: Lunar activities apply to broad scientific and exploration concerns.

Lunar science as described in this report has much broader implications than simply studying the Moon. For example, a better determination of the lunar impact flux during early solar system history would have profound implications for the evolution of the solar system, the early Earth, and the origin of life. A better understanding of the lunar interior would bear on models of planetary formation in general and the origin of the Earth-Moon system in particular. And exploring the possibly ice-rich lunar poles could reveal important information about the history and distribution of solar system volatiles. Furthermore, although some of the committee's objectives are focused on lunar-specific questions, one of the basic principles of comparative planetology is that each world studied enables researchers to better understand other worlds, including our own. Improving our understanding of such processes as cratering and volcanism on the Moon will provide valuable points of comparison for these processes on the other terrestrial planets.

Table 2 shows linkages between the science goals for the recommended lunar exploration program and broader scientific and applied concerns.

FINDING 1: Enabling activities are critical in the near term.

A deluge of spectacular new data about the Moon will come from four sophisticated orbital missions to be launched between 2007 and 2008: SELENE (Japan), Chang'e (China), Chandrayaan-1 (India), and the Lunar Reconnaissance Orbiter (United States). Scientific results from these missions, integrated with new analyses of existing data and samples, will provide the enabling framework for implementing the Vision's lunar activities. However, NASA and the scientific community are currently underequipped to harvest this data and produce meaningful information. For example, the lunar science community assembled at the height of the Apollo program of the late 1960s and early 1970s has since been depleted in terms of its numbers and expertise base.

> **RECOMMENDATION 1:** The committee urges NASA to make a strategic commitment to stimulate lunar research and engage the broad scientific community[1] by establishing two enabling programs, one for fundamental lunar research and one for lunar data analysis. Information from these two efforts, the Lunar Fundamental Research Program and the Lunar Data Analysis Program, will speed and revolutionize understanding of the Moon as the Vision for Space Exploration proceeds.

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[1] See also National Research Council, *Issues Affecting the Future of the U.S. Space Science and Engineering Workforce: Interim Report*, The National Academies Press, Washington, D.C., 2006.

TABLE 2 Relationship of Lunar Science Goals to Broad Scientific Areas

Science Goals	Astrobiology[a]	Planetary Science[b]	Early Solar System >4.0 Billion Years Ago[c]	Cosmo-chemistry[d]	In Situ Resource Utilization[e]	Human Habitation Issues[f]
Solar system impact flux	X	X	X			X
Planetary interiors		X	X	X		X
Planetary crusts	X	X	X	X	X	
Planetary volcanism		X		X	X	
Cratering process	X	X				
Regolith evolution	X	X		X	X	
Early Earth	X	X	X			
Polar areas	X	X		X	X	X
Atmosphere		X		X		X
Astrophysics			Awaiting further input.			
Earth science			Awaiting further input.			
Solar-terrestrial processes			Awaiting further input.			

[a] Astrobiology: Lunar investigations focused on early conditions in the inner solar system will have applications to astrobiology, because of its consideration of the conditions during the emergence of life on Earth.
[b] Planetary Science: Many of the processes that are available for study on the Moon, such as volcanism, impact, and regolith formation, are also of fundamental importance on other planets and small bodies of the solar system.
[c] Early Solar System: The Moon provides a unique window on early solar system processes, in particular the early impact history of the inner solar system.
[d] Cosmochemistry: Determining the bulk composition of the Moon will provide important information about the origin of the Earth-Moon system.
[e] In Situ Resource Utilization: Accomplishing the objectives of the science program will provide necessary information for assessing the distribution of lunar resources and establishing the most appropriate methods to extract them.
[f] Human Habitation Issues: Many of the objectives, such as more accurately determining the seismic activity of the Moon, will inform design considerations for lunar habitation, and all will play into the decision eventually of where to establish a permanent lunar outpost.

FINDING 2: Explore the South Pole-Aitken basin.

The answer to several high-priority science questions identified can be found within the South Pole-Aitken basin, the oldest and deepest observed impact structure on the Moon and the largest in the solar system. Within it lie samples of the lower crust and possibly the lunar mantle, along with answers to questions on crater and basin formation, lateral and vertical compositional diversity, lunar chronology, and the timing of major impacts in the early solar system.

Missions to South Pole-Aitken, beginning with robotic sample returns and continuing with robotic and human exploration, have the potential to be a cornerstone for lunar and solar system research. (A South Pole-Aitken sample return mission was listed as a high priority in the 2003 NRC decadal survey report *New Frontiers in the Solar System: An Integrated Exploration Strategy*.)

> **RECOMMENDATION 2:** NASA should develop plans and options to accomplish the scientific goals set out in the *New Frontiers in the Solar System: An Integrated Exploration Strategy*'s (NRC, 2003) high-priority recommendation, through single or multiple missions that increase understanding of the South Pole-Aitken basin and by extension all of the terrestrial planets in our solar system (including the timing and character of the early heavy bombardment).

FINDING 3: Determine the composition and structure of the lunar interior.

Determining the structure and composition of the interior of the Moon, from the outer layers of the crust to the deep core, will provide enormous insight into many of the highest-priority scientific questions. Long-duration geophysical stations (with broad-band seismometers, heat flow measurements, and precision tracking capability) implemented at multiple (six or more) sites are required to provide comprehensive subsurface information.

> **RECOMMENDATION 3:** Because a globally distributed network of many geophysical stations is critical for these investigations, an international effort should be pursued to coordinate the development of a standard, small set of key instruments (e.g., seismometer, thermal profiler, retro-reflector, etc.) and to cooperate in providing for its wide deployment across the Moon.

FINDING 4: Maximize the diversity of lunar samples.

Laboratory analyses of returned samples provide a unique perspective based on scale, precision, and flexibility of analysis and have permanence and ready accessibility. The lunar samples returned during the Apollo and Luna missions dramatically changed understanding of the character and evolution of the solar system. We now understand, however, that these samples are not representative of the larger Moon and do not provide sufficient detail and breadth to address the fundamental science themes outlined in Table 1. Laboratory analyses of returned samples provide a unique perspective based on scale, precision, flexibility, and permanence/accessibility.

> **RECOMMENDATION 4:** Landing sites should be selected that can fill in the gaps in diversity of lunar samples. To improve the probability of finding new, ejecta-derived diversity, every landed mission that will return to Earth should retrieve at a minimum two special samples: (a) a bulk undisturbed soil sample (200 g minimum) and (b) at least 1 kg of rock fragments 2 to 6 mm in diameter sieved from bulk soil. These samples would be in addition to those collected at specific high-priority sampling targets within the landing site.

FINDING 5: Proceed with lunar surface mission development and the site selection process.

Plans to return to the Moon will involve the selection of surface exploration sites. The selection process will involve, among many factors, scientific potential, ease of access, potential to conduct traverses, options for future build-up to an outpost or base, resource utilization potential, and explorer safety. Many of the science goals listed in Table 1 depend critically on site selection, although a given site might satisfy several requirements of several different goals. In the period under consideration for this report, both robotic and human sample return capabilities can be considered.

> **RECOMMENDATION 5:** Development of a comprehensive process for lunar landing site selection that addresses the science goals of Table 1 should be started by a science definition team. The choice of specific sites should be permitted to evolve as understanding of lunar science progresses through the refinement of science goals and the analysis of existing and newly acquired data. Final selection should be done with full input of the science community in order to optimize science return while meeting engineering and safety constraints.

FINDING 6: Understand the lunar polar deposits and environment.

Almost nothing is known about the sources of volatiles at the lunar poles and the processes operating on these volatiles. Additionally, there is almost no information about the physical properties of the lunar soils in permanently shaded regions. Finally, there is no knowledge of how robotic and human activities on the Moon will affect and change the unique and possibly fragile lunar polar environment.

> **RECOMMENDATION 6:** NASA should carry out activities to understand the inventory, lateral distribution, composition (chemical, isotopic, mineralogic), physical state, and stratigraphy of the lunar polar deposits. This understanding will be gained through analyses of orbital data and in situ data from landed missions in the permanently shaded regions. In situ studies should occur early enough in the lunar program to prevent substantial change in the polar environment due to robotic and human activities.

FINDING 7: Understand and characterize the lunar atmosphere.

The lunar atmosphere is the only surface boundary exosphere (SBE) in the solar system that is sufficiently accessible to study in detail. Despite many Apollo and Earth-based measurements, numerous aspects of the lunar atmosphere (e.g., composition, interaction processes) remain unknown. Furthermore, the lunar atmosphere is so extremely fragile that robotic and human activities can completely transform the nature—possibly permanently—of this pristine environment.

> **RECOMMENDATION 7:** To document the lunar atmosphere in its pristine state, early observational studies of the lunar atmosphere should be made, along with studies of the sources of the atmosphere and the processes responsible for its loss. These include a full compositional survey of all major and trace components of the lunar atmosphere down to a 1 percent mixing ratio, determination of the volatile transport to the poles, documentation of sunrise/sunset dynamics, determination of the variability of indigenous and exogenous sources, and determination of atmospheric loss rates by various processes.

FINDING 8: Evaluate the Moon's potential as an observation platform.

Observation from the Moon may be useful to astrophysics, studies of the Sun-Earth connection, Earth science, and some parts of astrobiology. There are uncertainties in the environmental benefits, disadvantages, potential mitigations, and costs of the Moon as an observation platform relative to alternate space sites, requiring a thorough study.

> **RECOMMENDATION 8:** The committee recommends that a thorough study be done by NASA to evaluate the suitability of the Moon as an observational site for studies of Earth, Sun-Earth connections, astronomy, and astrophysics.

FINDING 9: Establish strong ties with international programs.

The current level of planned and proposed activity indicates that almost every space-faring nation is interested in establishing a foothold on the Moon. Although these international thrusts are tightly coupled to technology development and exploration interests, science will be a primary immediate beneficiary. NASA has the opportunity to provide leadership in this activity, an endeavor that will remain highly international in scope.

> **RECOMMENDATION 9:** NASA is encouraged to explicitly plan and carry out activities with the international community for scientific exploration of the Moon in a coordinated and cooperative manner. The committee endorses the concept of international activities as exemplified by the recent "Beijing Declaration" of the 8th International Conference on Exploration and Utilization of the Moon.

5
Related Findings and Recommendations

In the course of developing the science goals and priorities, it became evident to the committee that the successful accomplishment of science at all stages in the Vision for Space Exploration requires that NASA pay early attention to factors that are essential adjuncts.

FINDING 1R: Optimize the partnership between NASA's Exploration Systems Mission and Science Mission Directorates.

The Vision for Space Exploration has created new opportunities for the accomplishment of space science associated with lunar human exploration. This requires a strong collaboration between the Exploration Systems Mission and Science Mission Directorates. Historically (Apollo, Skylab, ASTP, Shuttle/Spacelab) there have been different management approaches to accomplish such a collaboration; some have been more successful than others. Today there does not appear to be an appropriate management system in place to ensure the best possible integration of human and robotic exploration.

> **RECOMMENDATION 1R:** Prior Space Studies Board reports examined management approaches to the integration of human exploration and space science. They found that an optimum approach consisted of establishing a science management office within (today) the Exploration Systems Mission Directorate, reporting jointly to the Science Mission and Exploration Systems Mission Directorates. Such an office should be established as soon as possible to ensure the productive involvement of science planning and implementation ab initio.

FINDING 2R: Identify and develop lunar-specific advanced technology and instrumentation.

To fully achieve individual science goals that are amenable to in situ analysis, instrumentation, or field observations, close attention must be paid to the further development of technology and instruments designed specifically for the Moon as well as for utilization at Earth-based curatorial facilities in order to realize the full capabilities provided by robots and astronauts in the field.

> **RECOMMENDATION 2R:** NASA should create an advanced technology program to develop lunar-specific capabilities that are critical to successful implementation of the lunar science strategy outlined in Table 1. This program should tap the creativity of the engineering and science communities to address development of robotic and instrumentation capability to meet needs that at present are unmet.

FINDING 3R: Plan curatorial and principal investigator facilities for new lunar samples.

Lunar samples returned to Earth in the next two decades could strain the current NASA curatorial facilities and require new and/or modified facilities and procedures. It is anticipated that the volume of new material may exceed that returned by Apollo. Further, both curation and community analyses will require new or refined techniques and instrumentation.

> **RECOMMENDATION 3R:** NASA should evaluate the future needs of curatorial facilities for the collection of new lunar samples. The state and availability of instrumentation for both curation and analyses should be assessed. Such a study should include representatives of the science community in detailed planning of an appropriate strategy.

FINDING 4R: Optimize astronaut lunar field investigations—an integrated human/robotic approach.

Elements of the recommended lunar science will require more extensive geologic and geophysical traverses and complex instrument emplacement than on Apollo. Detailed planning must be based on all data available for the sites being studied and on a clear understanding of astronaut capability. Extensive and close cooperation between lunar scientists, mission developers, and operations planners will be required, as will integration of science with other Vision goals. Because robotics capability has increased greatly since Apollo, astronaut efficiency can be significantly improved with pre-mission and mission use of a new generation of traverse capability, robotic assistants, and autonomous/teleoperated robotic systems.

> **RECOMMENDATION 4R:** NASA should provide astronauts with the best possible technical systems for conducting science traverses and emplacing instruments. An integrated human/robotic program should be developed using robotic assistants and independent autonomous/teleoperated robotic systems. The capabilities of these systems should be designed in cooperation with the science community and operations planning teams that will design lunar surface operations. Extensive training and simulation should be initiated early to help devise optimum exploration strategies.

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Appendixes

A
Statement of Task

Science Goals and Priorities for Lunar Exploration

Background

The Moon is the first waypoint for human exploration in the Vision for Space Exploration. While not premised primarily on science goals, a well-planned and executed program of human exploration of the Moon and of the robotic missions that will precede and support it offers opportunities to accomplish important scientific investigations about the Moon and the solar system beyond.

NASA is aggressively defining and implementing the first missions in a series of robotic orbital and landed missions, the Lunar Precursor and Robotic Program (LPRP) of the Exploration Systems Mission Directorate (ESMD). The LPRP is intended to obtain essential supporting data for precursor robotic and human landings planned for 2018 and shortly thereafter. The first LPRP mission, the Lunar Reconnaissance Orbiter, is already in implementation and scheduled for a 2008 launch. A second mission, a lander, is in pre-formulation. The LPRP program office is currently developing an overall LPRP program architecture. Payloads for these forerunner robotic missions respond primarily to requirements for supporting robotic and future human landings, but may offer also opportunities to acquire scientifically valuable information as well. In order to realize this benefit from the LPRP series, NASA needs a comprehensive, well-validated, and prioritized set of scientific research objectives for the Moon.

Looking beyond the robotic precursor missions, science goals will also be needed to inform early decisions about system design and operations planning for human exploration of the Moon. In a near-term program of sortie-mode human landings with their capability for in situ instrument deployment and operation as well as informed sample return, the most immediate candidates for investigation are lunar science and the history of the solar system, including the history of the Sun. Design and planning for human exploration will need insight into the types of investigations that astronauts on the Moon might carry out as well as projections of necessary equipment and operations. The point of departure for this planning would be the Apollo program. However, NASA's current plans envisage spacecraft with superior capabilities and endurance to those of the Apollo program. For example, the new lunar landing vehicle may initially support a crew of four on the surface of the Moon for a week, compared to the Apollo landing vehicle's crew of two and surface stay time of 2-3 days.

For longer range human presence on the moon, the scope of science is potentially broader, possibly including emplacement or assembly and maintenance and operation of major equipment on the lunar surface. Expanded future presence could evolve from the near-term program by offering permanent, versus sortie, human presence and by a greatly increased landed mass on the Moon. Follow-on lunar-based science might include not only intensified lunar surface research, but also possibly observations of the Earth and of the universe beyond the solar system. Eventually, analyses and trade studies on science efficacy and cost benefit will be required in order to understand the value of the Moon as a site for such undertakings.

Study Scope

The current study is intended to meet the near term needs for science guidance for the lunar component of the Vision for Space Exploration. In the context of the above background, the *primary goals* of the study are to:

1. Identify a common set of prioritized basic science goals that could be addressed in the near-term via the LPRP program of orbital and landed robotic lunar missions (2008-2018) and in the early phase of human lunar exploration (nominally beginning in 2018); and
2. To the extent possible, suggest whether individual goals are most amenable to orbital measurements, in situ analysis or instrumentation, field observation or terrestrial analysis via documented sample return.

Secondary goals:

3. Goals and activities oriented toward ESMD requirements, for example, LPRP characterization of the lunar environment of value to human safety and in situ resource utilization (ISRU), should be analyzed, to the extent that these characterization requirements are provided by ESMD. These should be tabulated separately, but areas of overlap between basic science goals and these ESMD requirements should be noted as synergistic opportunities.
4. It is not intended that the current study address in depth more ambitious future opportunities that would entail assembly of large and complex research apparatus on the Moon. Examples are major lunar astronomical observatories or Earth observation systems that might follow systems currently in formulation or development. Implementation of such systems could become possible after the initial phases of human exploration. Science goals for astronomy and astrophysics are already provided by the NRC reports *Astronomy and Astrophysics in the New Millennium (NAP, 2000*) and *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (NAP, 2003)*. Earth system science and applications goals will be articulated in the new NRC decadal survey under development for this area and due for completion in late 2006. In these areas, the present study should limit itself to collecting and characterizing longer term possibilities, if any, that deserve feasibility and cost/benefit analysis in a future study.

The *science scope* of study goals 1 and 2 should encompass:

- The history of the Moon and of the Earth-moon system;
- Implications for the origin and evolution of the solar system generally, including the Sun; and
- Implications of all of these for the origin and evolution of life on Earth and possibly elsewhere in the solar system.

Applied laboratory research in life sciences or materials or physical science in the lunar low-gravity environment oriented toward human Mars exploration requirements are not within scope of the task, but could be addressed in a future study.

Where appropriate, activities recommended for implementation within the lunar exploration component of the Vision for Space Exploration should be compared to other means of implementing the same scientific goals. There is a broad spectrum of science ideas being discussed for the lunar program at this time. The intent is that the committee focus on the strongest and most compelling ideas that come before it. There is a broad and expert community of planetary scientists with special interest in the Moon and lunar science. This community will make scientifically persuasive arguments that certain lines of inquiry can be uniquely well-conducted on the Moon. It is anticipated that the goal prioritization requested for this study will differentiate between science investigations that can only be done on the Moon, those that could potentially be competitively conducted on the Moon depending on analyses of cost and technical factors, and investigations for which current knowledge and forecasted capabilities lend little support for lunar implementation. It is essential that NASA adopt the very strongest science program possible for the Moon right from the outset because advocated weak science would be questioned and could jeopardize the entire lunar program.

While premised on a framework of essentially flat science budgets in the near term, the study may consider also the possibility of expanded budgets for lunar science in the post-2010 time frame, after shuttle retirement.

Because lunar exploration within the Vision for Space Exploration is envisioned as a broadly international undertaking, the study should attempt to factor in interests and perspectives of foreign investigators and/or agency officials by inclusion of some of these as panel members and/or as briefers, as appropriate.

Deliverables and Schedule

It is anticipated that development of the study products will be undertaken via a two phase process consisting of (1) an initial review and integration of goals and priorities in existing NRC and other documentation and (2) a science community outreach program to validate, update, and extend the findings of this review to support planning for potential follow-on LPRP missions and astronaut missions during the sortie phase of human lunar exploration.

The final report of the study should contain the following primary elements:

1. A brief summary of the current status and key issues of scientific knowledge concerning the origin and evolution of the Moon and related issues in solar system evolution;
2. Basic science goals and priorities for research within scope of the study task that are contained in NRC decadal surveys relevant to lunar exploration, as expanded and extended.

Insofar as is possible, the final report should also contain:

3. A summary of the scientific measurements and LPRP activities necessary to support the safe return of humans to the Moon, to the extent that relevant requirements are provided to the NRC by ESMD; and
4. A high-level survey of possible future activities and infrastructure that could address science objectives lying outside the current study scope but deserving of feasibility and cost/benefit evaluation for potential implementation during a long-term human presence on the Moon.

An interim description of basic science goals and priorities (items 2 and 3 above) should be released for community discussion and preliminary NASA planning use, if possible by *August 31, 2006*. Delivery at this time would enable its use by NASA to inform finalization of the fiscal year 2008 budget proposal, and to support an exploration strategy drafting meeting being planned by ESMD for mid-September 2006 and a NASA Advisory Council Science Committee workshop planned for later in 2006.

A prepublication version of the final report should be delivered by *May 31, 2007*, in order to be of maximum value during formulation of the fiscal year 2009 budget proposal.

The present task may not extend beyond July 14, 2007. Delivery of the edited final report will be negotiated once the study is in progress and may be supported by a task issued under the follow-on contract.

B
Acronyms and Abbreviations

ALSEP—the Apollo Lunar Surface Experiments Package
ASTP—the Apollo-Soyuz Test Project, a joint U.S.-U.S.S.R. mission
ATP—NASA's Advanced Technology Program
Chang'e—a Chinese National Space Administration lunar orbiter
CHEX—the NRC's Committee on the Human Exploration of Space
ESMD—NASA's Exploration Systems Mission Directorate
EVA—Extravehicular activity
ISRU—in situ resource utilization
KREEP—lunar basalts that are rich in potassium, rare-earth elements, and phosphorus
LCROSS—the Lunar Crater Observation and Sensing Satellite, a secondary payload to be launched with the Lunar Reconnaissance Orbiter
LHB—the Late Heavy Bombardment period, about 3.9 billion years ago
LPRP—the Lunar Precursor and Robotic Program of the Exploration Systems Mission Directorate
LRO—NASA's Lunar Reconnaissance Orbiter
LSAM—NASA's Lunar Surface Access Module
Lunar A—a Japanese Aerospace Exploration Agency lunar mission
M3—Moon Mineralogy Mapper, an imaging spectrometer on the Indian Space Research Organization's Chandrayaan-1 lunar mission
MER—NASA's Mars Exploration Rover
SBE—surface boundary exosphere
SELENE—Selenological and Engineering Explorer, a Japanese Aerospace Exploration Agency lunar orbiter
SIM—the Apollo Scientific Instrument Module, which contained panoramic and mapping cameras, a gamma-ray spectrometer, a laser altimeter, and a mass spectrometer
SMART-1—Small Missions for Advanced Research in Technology, a European Space Agency lunar mission
SMD—NASA's Science Mission Directorate
SPA—the lunar South Pole-Aitken basin
Vision—NASA's Vision for Space Exploration