Summary of *The Moon Beyond 2002: Next Steps in Lunar Science and Exploration*: A Lunar Science Workshop held in Taos, New Mexico on September 12 – 14, 2002

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1. Introduction

The past ten years have seen a renaissance in lunar science. The *Clementine* and *Lunar Prospector* missions have provided critical new data about the global composition and physical state of the lunar surface, while continuing studies of lunar samples are expanding our understanding of the lunar interior, regolith and surface processes. All of these new data are in turn stimulating new efforts at modeling the composition and physical state of the lunar surface and interior with ever increasing detail. New missions to shed further light on the lunar surface and interior are being implemented by the Japanese and European space agencies. Activities to highlight the new data sets and efforts to integrate the results have been promoted by the *New Views of the Moon* (NVM) lunar science initiative. This initiative has successfully brought together planetary scientists from a wide variety of disciplines for dedicated lunar science workshops, special sessions dedicated to lunar science at the annual Lunar and Planetary Science conference, and special lunar science issues of *Journal of Geophysical Research*.

One of the conclusions that has been reinforced from all of this recent work is that despite a common perception of simplicity, the Moon is a complicated planetary body. The new information that has been gathered and assimilated has highlighted many aspects of the Moon's formation, evolution, and current state that remain mysteries. We know more about the Moon through samples and remote sensing than any other planetary body besides the Earth. However, the more we learn about the Moon through continued exploration, the more we uncover complexity that is perhaps surprising given its small size and apparent rapid and early cooling history. What we have learned about the Moon and the complexity that has been revealed has implications for how we can understand – through remote, in-situ, and sample studies - other planetary bodies that may be even more complex. Our study of the Moon can therefore serve as a case study for how we explore other parts of the solar system.

In light of these recent advances, the workshop *The Moon Beyond 2002: Next Steps in Lunar Science and Exploration* was held in order to focus the planetary science community on the following: 1) What are the key questions that should now be addressed to advance lunar science and exploration? and 2) What actions should the planetary science community carry out to best answer these questions? This document summarizes major highlights of this workshop.

2. Workshop Attendance, Organization and Format

A total of 102 scientists, engineers, and others attended "Next Steps in Lunar Science and Exploration" that was held on September 12 – 14 at the Taos Ski Valley Resort Center outside of Taos, New Mexico. A list of workshop participants is given at the end of this summary. The first day of the meeting coincided with the 40th anniversary of John F.

Kennedy's famous speech at Rice University when he justified and gave inspiration to the Apollo program to the Moon with the words[1]:

> "We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone."

Those words provided the backdrop for the meeting as participants discussed the next steps of lunar science and exploration.

The main scientific portion of the meeting consisted of seven sessions over two and a half days. Of these, six sessions contained invited and contributed oral presentations; one session contained contributed poster presentations. In addition to the scientific sessions, there were two geologic field trips of the Rio Grande Gorge area, which was one of the training sites for the Apollo 15 astronauts. The trips were led by Apollo program geologists Gordon Swann and Bill Muehlberger, and Apollo 17 astronaut Harrison Schmitt. The purpose of these trips was to study the landforms, including the volcanic stratigraphy, in much the same way as the Apollo astronauts did in their training. Almost 3/4 of the workshop attendees participated in the trips.

NASA's Office of Space Flight through the Human Exploration and Development in Space program sponsored and funded a student grant program for *Next Steps in Lunar Science and Exploration*. This program provided full funding for thirteen undergraduate and graduate students to attend the workshop. Among these, four undergraduate students from the University of New Mexico were funded to attend the meeting and to assist with the operation of the presentation equipment (overheads, slides, computer projector).

3. Overview of Scientific Program

Four of the seven scientific sessions were organized under the topics of *Lunar Polar Deposits*, *Investigating the Lunar Surface and Regolith*, *Lunar Composition and Remote Sensing*, and *Lunar Core, Interior, and Impacts*. These sessions were bracketed at the beginning and end of the workshop by sessions focusing on an *Overview of Lunar Science and Exploration* and *Future Lunar Missions*. The purpose of this ordering was to start the workshop with an overview of current objectives, ideas, and strategies for conducting lunar science and exploration. Then during the majority of the workshop, contributed presentations (including posters) focused on current lunar science research as well as how this research addresses the important questions of lunar science that have yet to be answered. The final session summarized and concluded the workshop with detailed mission plans in various stages of development that seek to answer many of the questions discussed throughout the workshop. All sessions were set up to have ample time for questions and discussion.

A proceedings publication for the workshop, in the form of one-page extended abstracts, was made available at the workshop. Copies of the abstract volume can be obtained online or in hard copy through the LPI[2]. Because this abstract volume provides the best

and most complete record of what was presented at the workshop, its details will not be presented here. Rather, a summary of some highlights is given to illustrate the breadth and depth of what was discussed.

3.1 Overview of Lunar Science and Exploration

The invited opening talk by James Head of Brown University set the stage for the entire workshop by arguing that understanding the Moon is foundational for understanding planetary geological processes elsewhere. This theme was reiterated many times by presenters throughout the workshop. In addition, it was emphasized throughout the meeting that progress in lunar science and exploration should be achieved as part of an ongoing program and not just mission by mission. Other topics in the opening session described how to study and make use of lunar resources (Taylor, Criswell), innovative approaches to returning to the Moon with both instrumentation and humans (Cooke, Nozette), and how humans should operate once they are back on the Moon (Duke).

The opening session concluded with a presentation by Carle Pieters of Brown University describing the results of the recently released National Research Council's Solar System Exploration Decadal Study[3]. The goal of the Decadal Study was to establish a science-driven set of exploration priorities for NASA planetary science for the next ten years. One of the highlights of the decadal study is that a sample-return mission to the Moon's South Pole-Aitken Basin is listed as second highest priority for the medium class ($350 – 650 million) New Frontiers missions. As a consequence, one of the near-term goals for the lunar science community (and which was begun at this workshop) is to discuss and refine the science requirements and mission scenarios for a potential SPA Basin sample-return mission. This subject was further discussed during the last day in the *Future Lunar Missions* session.

In addition to the scheduled presentations, an special presentation on potential future lunar exploration was given by Paul Spudis (Johns Hopkins University/Applied Physics Laboratory) at the end of the Friday scientific sessions. While not originally part of the *Overview of Lunar Science and Exploration*, Paul Spudis' talk followed a similar theme by arguing that a manned lunar based could be established on the Moon in a relatively short time (~5 years) with existing technology. Part of the basis of this assertion was described by Doug Cooke (JSC) in the opening session, where he described how missions beyond low-Earth orbit can be simplified through the applications of advanced technology and new mission designs. Further details about Paul Spudis' presentation can be obtained directly from Paul at paul.spudis@jhuapl.edu, since it is not included in the abstract volume.

3.2 Lunar Polar Deposits

The afternoon of Thursday, September 12 had two different sessions. The first covered issues of the polar hydrogen deposits that have been interpreted by some to be in the form of water-ice. Presentations in this session discussed identifying and measuring the amount of permanent shade in the polar regions (Bussey), alternative explanations for the form of the hydrogen enhancements (i.e., solar wind implanted hydrogen) (Vondrak and Butler), and issues of future exploration, such as obtaining better measurements of polar

topography (Smith) and understanding the resource potential of the hydrogen deposits (Blair). David Smith emphasized the need (and capability) to determine topography with orders of magnitude better spatial and vertical resolution than is currently available for the entire Moon as well as for the polar regions. Discussions in this session highlighted the need for future missions to better measure and characterize the composition, concentration, and extent of the lunar polar hydrogen deposits. One such mission (Polar Night) was described in detail by Paul Lucey in the Saturday morning session.

3.3 Investigating the Lunar Surface and Regolith

The second session of Thursday afternoon described remotely sensed and sample measurements of the lunar surface and regolith. Highlights of this session included new analyses of sub-meter Lunar Orbiter imaging data (Wilcox) and Lunar Prospector global composition data. In particular, new results were presented for global Mg, Al, Ti, and Fe abundances using data from the LP gamma-ray and neutron spectrometers (Prettyman) and comparing these data to lunar sample compositions (Vaniman). New Mg-rich provinces in the highlands north of mare Frigoris and northwest of Crisium basin were identified with these data. Furthermore, evidence was reported of recent gas release events using data from the LP Alpha-Particle Spectrometer (Lawson). In regards to sample studies, Larry Taylor suggested that nanophase iron may not necessarily occur from hydrogen reduction but from the remelting of previously vapor-deposited nanophase iron. Finally, John Armstrong presented the possibility that ancient Earth meteorites may exist on the Moon and outlined a method for their identification.

3.4 Poster Session

The poster session on Thursday evening contained a wide variety of presentations (22 posters) on different topics ranging from implementation of current and future lunar missions and instrumentation (Araki, Frassanito, Iwata, Lepper, Rodriguez, Sarrazin, Miller [late submission]), using the Moon as a base for a variety of scientific endeavors (Takahashi, van Susante, Young), to more detailed lunar science topics (Asmar, Byrne, Chabot, Dukes, Hagerty, Hooper, Karner, Mitchell, Norman, Petro, Stegman).

3.5 Lunar Composition and Remote Sensing

On Friday, September 13, there were two sessions. The morning session, *Lunar Composition and Remote Sensing*, contained a variety of presentations on topics ranging from the bulk composition of the Moon (Taylor and Jolliff), to studies of current Clementine and Lunar Prospector data (Gillis, Hawke, Hiesinger, Lawrence), to future work that will be done in the area of spectral reflectance measurement from a theoretical (Lucey) and experimental viewpoint (Haruyama). One topic that generated discussion was the attempt to better understand the Moon's bulk composition. Brad Jolliff and Jeff Taylor pointed out there is still uncertainty and disagreement regarding important details of the Moon's bulk composition. This is an important issue as the Moon's bulk composition is intimately related to the original formation and evolution of the Moon and has implications for understanding the origin, composition, and early evolution of the Earth. Both presentations emphasized that global seismic measurements, global Al and Mg measurements, and sample measurements of the lower crust (i.e., SPA basin) would go far to help resolve key uncertainties in understanding the Moon's bulk composition.

3.6 Lunar Core, Interior, and Impacts

The Friday afternoon session of *Lunar Core, Interior and Impacts* contained a diverse set of presentations covering topics ranging from our understanding of the Moon's formation (Righter) and basin impacts (Peterson) to the ages and effects of basin impacts (Norman, Fernandes, Korotev, Spudis). Discussions of the nature and composition of the Moon's core were presented by Kevin Righter and Lon Hood. The role of basin impacts in the creation and destruction of surface magnetic fields was discussed by Jasper Halekas and Lon Hood. While clear systematic trends have emerged in the Lunar Prospector magnetic field data (i.e., magnetic fields concentrated at the antipodes of basins and low magnetic fields at the basins), a definitive understanding of how these fields were created remains elusive. Paul Spudis showed orbital composition data to support the idea that a concentration of basin ejecta at the antipodes of basins is possible. The topic of obtaining new samples from the western Procellarum mare basalts was discussed by James Whitford-Stark in the context of obtaining deep-seated samples from one of the many rilles in that region. This followed on presentations earlier in the workshop that advocated western Procellarum volcanic plains as desirable sample locations because of the region's thorium and iron enrichment (Lawrence), unusual titanium abundances (Elphic), and, in some places, young ages (Hiesinger). Finally, a number of presentations discussed the ages of basins and samples (Norman, Fernandes, Korotev), a topic critical to the ongoing discussion of whether the era of large-scale impacts on the Moon (and Earth) ended with a major "terminal cataclysm" at ~3.9 Gy.

3.7 Future Lunar Missions

The final session on Saturday, September 14 was devoted to a discussion of future lunar missions in various stages of development. Of the eight talks, seven described different missions that could address and answer various questions of lunar science. The most mature missions were those from the European and Japanese space agencies. Bernard Foing updated the community on the status of the European Space Agency's (ESA) SMART-1 mission. This is a technology demonstration mission that will also carry out lunar science and is expected to launch sometime in 2003 as a payload on an Ariane rocket. Lunar science highlights of SMART-1 include a multiband spectral reflectance imager and a new X-ray spectrometer. Both of these instruments will make improved measurements of the lunar surface and composition. There were two Japanese missions that were described by Hitoshi Mizutani. The first, called Lunar-A, is expected to launch sometime in 2003. It carries two hard-landing penetrators instrumented with seismometers and temperature probes. The goal of the mission is to emplace one penetrator each on the near and far sides of the Moon to gather seismic and heat flow measurements. The scientific goal of the mission is to gain a better understanding of the internal structure and composition of the Moon, particularly to test for a lunar core. The second Japanese mission described by Prof. Mizutani is called SELENE. This ambitious mission will seek to make comprehensive compositional and geophysical measurements from orbit using 12 separate instruments. SELENE is currently scheduled to launch in 2005.

The remaining presentations in the *Future Lunar Missions* session described mission concepts that represent a diverse set of ideas for future lunar science. Paul Lucey described the Polar Night mission, a Discovery class mission with the goal of better identifying the location of the polar hydrogen deposits and measuring and characterizing the composition of these deposits. One point made by Paul is that even though this mission's destination is the Moon, it is also generally related to solar system science as the lunar polar deposits have likely preserved a record of solar system volatiles over the past billion or so years. Clive Neal described a mission concept of deploying a larger number of seismic stations than is being done with Lunar-A. Such a mission would provide key geophysical constraints on the detailed structure and composition of the lunar crust and mantle using a network of modern, miniaturized, long-lived seismometers. Todd Ratcliff summarized the current state of lunar laser ranging, which precisely measures the distance between Earth and Moon, and can provide detailed information about the properties and structure of the deep lunar interior and the Moon's orbital dymanics. While techniques are continually being improved for obtaining and analyzing data from the current reflectors that were placed on the lunar surface during the Apollo program, one major improvement to this field of study (at a potentially low cost) would be to add additional surface reflectors on any future near-side landers.

Finally, the last two presentations by Chip Shearer and Mike Duke both discussed future sample-return missions. Chip Shearer discussed the idea that future robotic sample missions will likely return a relatively small amount of material compared to what was returned with the Apollo program. Yet even with small sample caches, there are many scientific questions that can be answered definitively using advanced laboratory instrumentation. In particular, determinations with sufficient accuracy to advance our understanding of the volcanic and impact chronologies, and other isotopic and trace-element measurements, as well as techniques involving high magnification or special sample preparation such as SEM and TEM measurements, still require analysis in state-of-the-art laboratories on Earth. However, comments were also made that if science requirements can be well defined for some subset of in-situ measurements, this would push creative instrument designers to develop increasingly capable space-based instruments, such as may be needed for in-situ analysis of materials that will not be easily sampled and returned to Earth without degradation (e.g., polar frozen volatile deposits).

The final presentation, given by Mike Duke, described current concepts for a future South Pole-Aitken Basin Sample Return (SPA-SR) mission. As highlighted in the Solar System Decadal Study[3], this mission has a high priority because samples from SPA Basin would 1) enable determination of the rock types from the Moon's lower crust and/or mantle, which would help to increase understanding of the formation and differentiation processes that occurred early on the Moon; and 2) dating samples of impact melt/breccia from the SPA basin forming event would provide a critical test of the late, heavy bombardment/cataclysm hypothesis and would constrain the timing of such a bombardment that presumably affected the evolution of the entire inner solar system.

Mike Duke and others raised two major issues in regards to the SPA-SR mission: 1) The lunar science community needs to discuss and refine major science goals for a SPA-SR

mission so that when NASA releases an Announcement of Opportunity for the New Frontiers line of missions, there is a general consensus on the best science goals for the mission; 2) To reach such a consensus, there needs to be vigorous discussion within the scientific community regarding how the science goals can best be achieved through different mission scenarios. As a template, Mike Duke presented two strawman mission scenarios. The first scenario uses two simple landers that will select nearby lunar soil from two different SPA basin locations and return both sample caches to Earth. The second scenario uses a more sophisticated lander plus a possible rover that would spend more time selecting a single sample cache before returning it to Earth.

Two action items resulted from the SPA-SR discussion. These were the following: First, the lunar community should continue the discussion that was started at this workshop to better refine the science goals, requirements, and mission scenarios for a SPA-SR mission. At a minimum, this can, and should be done through the Lunar List Server moderated by Clive Neal at Notre Dame University[4]. There was also discussion of setting up a dedicated web site where interested individuals could participate in discussions and share information about a SPA-SR mission. If and when this is done, it will be announced using the lunar list server. Second, there was a proposal to hold a special SPA-SR session at the 2003 Lunar and Planetary Science Conference. This session will focus on science of the SPA basin.

4. Overall Comments and Lessons Learned

The general perception from most who attended *Next Steps in Lunar Science and Exploration* is that it was a productive and enjoyable meeting. Specific comments include the following points. First, smaller meetings of around 100 attendees tend to be very productive as all presentations can be made in a single session. In addition, it is very important to provide ample time for questions and discussions. Second, this workshop was set up more like a retreat, such that participants spent meals and non-session time together. This enhanced the opportunity to have individual discussions that are very valuable in expanding and elucidating ideas that are discussed in the more formal sessions. Finally, a number of participants expressed appreciation for the multi-disciplinary nature of the meeting. While this meeting was primarily a lunar science meeting, it nevertheless brought together people from many different backgrounds (i.e., geology, physics, engineering) in a way that all learned from each other. Finally, one of the main lessons learned from the workshop is that computer projection equipment that works quite well at an altitude of 7500 feet (2200 m) has major thermal control problems at 9500 feet (2800 m). Only with the great efforts of the UNM students Neyda Abreu, Rae Carey, Jennifer Edmunson, Melissa Fittipaldo, and Bob Bohannon of Taos Ski Valley, was a procedure set up (ice packs and a cannibalized computer fan) that allowed the computer projector to be adequately cooled.

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References

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[2]*The Moon Beyond 2002: Next Steps in Lunar Science and Exploration*, Contribution No. 1128, Lunar and Planetary Institute, Houston; http://www.lpi.usra.edu/meetings/moon2002/pdf/program.pdf.

[3]New Frontiers in the Solar System: An Integrated Exploration Strategy, Solar System Exploration Survey, Space Studies Board, National Research Council; http://www.nationalacademies.org/ssb/newfrontiersfront.html.

[4]Lunar List Server, contact Clive Neal at Neal.1@nd.edu.

List of Participants for *The Moon Beyond 2002: Next Steps in Lunar Science and Exploration*

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