National Aeronautics and Space Administration

NASA LUNAR SCIENCE INSTITUTE

A THREE YEAR REPORT

2012

Edited by

David Morrison, NLSI Senior Scientist

Teague Soderman, NLSI Senior Science Writer

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INTRODUCTION

NLSI Central is located in a historic building in the NASA Research Park at Ames Research Center. The building is named the Blumberg Center for Science Innovation, honoring Barry Blumberg, the Nobel-prize winning scientist who contributed greatly to the success of both the NASA Astrobiology Institute and the NASA Lunar Science Institute.

INTRODUCTION

The NASA Lunar Science Institute (NLSI) is proud to present this summary of the accomplishments in its first three years of existence. This report contains an introduction to the Institute, executive summaries highlighting the accomplishments of NLSI's seven U.S. teams, and a bibliography of scientific publications produced during the time period covered by this report.

The NLSI is an innovative virtual research organization that leverages expertise from the science and exploration communities to support NASA's goals in lunar science (as outlined by the National Research Council and relevant NASA studies) as well as human exploration beyond low Earth orbit. The Institute also contributes to building a lunar science community, training the next generation of lunar scientists, and communicating lunar science with educators and the public.

The short existence of the NLSI has seen a blooming of lunar science, fueled in part by data from several scientific missions to the Moon (Chang'e, Kaguya, Chandrayaan, Lunar Reconnaissance Orbiter [LRO], Lunar Cratering Observation and Sensing Satellite [LCROSS], and the Gravity Recovery and Interior Laboratory [GRAIL]). New professional organizations have been formed to support lunar science, and sessions on the Moon have proliferated at the Lunar and Planetary Science Conference, the NLSI-sponsored Lunar Science Forum, and meetings of scientific societies such as the AAS Division for Planetary Sciences and American Geophysical Union. The increase in the number of students who have gravitated toward careers in lunar science is especially gratifying. The Institute has substantially re-energized the lunar community.

NLSI History and Organization. The NLSI was founded in March 2008, and seven member teams (see Table 1) were selected a year later through a highly competitive, peer reviewed process from proposals submitted to NASA. The Institute is based on the premise that exploration and planetary science are fundamentally intertwined; exploration enables science, but basic scientific understanding is foundational to safe, effective, and efficient human exploration. While the focus is on the Moon, NLSI scientists also study

Investigation Title	Team Leader	Institution
Understanding the Formation and Bombardment History of the Moon	**William Bottke**	Southwest Research Institute, Boulder, CO
Exploring the Cosmos From the Moon	**Jack Burns**	University of Colorado, Boulder, CO
Science and Exploration of the Lunar Poles	**Ben Bussey**	Johns Hopkins University/ Applied Physics Lab, Laurel, MD
Dynamic Response of the Environment at the Moon	**William Farrell**	NASA Goddard Space Flight Center, Greenbelt, MD
Colorado Center for Lunar Dust and Atmospheric Studies	**Mihaly Horanyi**	University of Colorado, Boulder, CO
Impact Processes in the Origin and Evolution of the Moon: New Sample-Driven Perspectives	**David Kring**	Lunar and Planetary Institute, Houston, TX
The Moon as Cornerstone to the Terrestrial Planets	**Carle Pieters**	Brown University, Providence, RI

Table 1. NLSI U.S. Teams.

lunar science within a broader context of both planetary science and future human exploration beyond low Earth orbit.

The NLSI is modeled on the successful NASA Astrobiology Institute (NAI), which pioneered the concept of a virtual scientific institute. Like NAI, NLSI consists of a distributed network of competitively selected teams, managed and directed by a small central office. The NLSI Central Office is located at NASA Ames Research Center, Moffett Field, Calif. A virtual Institute is complementary to both individual research and analysis grants and the establishment of a "bricks and mortar" organization. First, providing funding to existing research institutions leverages past investments ranging from research infrastructure to student training. Also, flexibility and stability— essential to maximizing efficiency across teams— are achieved through longer support periods with larger funding awards than provided through small R&A grants to a single researcher. Second, a virtual Institute integrates scientific research across both geography and disciplines; the products exceed the sum of the individual efforts and often cannot be foreseen. Third, a virtual Institute requires minimal overhead, with most of the resources going directly to the distributed research teams.

Each NLSI team brings together scientists from multiple organizations who have related capabilities and interests. The initial seven teams include more than 180 individual scientists and future researchers. The Institute also partners with international organizations, both research institutions (Affiliate partners) and government-based organizations (Associate partners) on a no-exchange of funds basis. The current international teams represent Canada, Germany, Israel, Korea, The Netherlands, Saudi Arabia, and the United Kingdom.

NLSI Goals. The prime product of the NLSI is research, disseminated to the community through professional publications, conferences and other methods including virtual workshops and webinars. The three-year bibliography included in this summary provides concrete evidence of the Institute's scientific contributions. The NLSI also serves as a community leader through sponsorship of conferences and activities focused on lunar science and exploration. The Institute is integrated with the NASA Advisory Council's Lunar Exploration Analysis Group (LEAG) through representation on the LEAG steering committee and executive group. In support of the virtual institute concept, NLSI is exploring innovative ways of using information technology for communications and scientific collaboration between geographically disparate teams. In addition to research, the Institute supports a robust program to communicate the excitement of science and exploration to teachers, students, and the public, and it develops programs to train the next generation of space science explorers.

Key Scientific Questions for Lunar Science*
• How did the Moon form and how did its interior structure arise?
• How has the impact history of the Earth-Moon system been recorded on the lunar surface?
• How have volcanic process on the Moon been initiated over lunar history and how do the volcanic flows reflect the interior composition?
• How have solar processes and space weather altered the lunar surface over time and been recorded in the lunar regolith?
• How will the lunar environment (e.g., dust) affect surface operations and influence designs for living on the Moon?
• What are the environmental conditions and the volatile content of the lunar poles?
• How will increased human activities alter the lunar environment?
• How can life from Earth adapt to long stays on the Moon?
• How can the Moon be used as a platform to advance important science goals in astronomy, Earth observation, and basic physics?

** From Section 5.1.1 Science and Technical Merit of the 2008 NLSI Cooperative Agreement Notice (CAN).*

For the NLSI, lunar science is broadly defined to include studies:

- ***Of the Moon:*** Investigating the composition, structure and history of the Moon as each relates to the evolution of the Earth, Moon and Solar System.

- ***On the Moon:*** Investigations of the effects of lunar material and the environment on terrestrial life and robotic equipment.

- ***From the Moon:*** Exploring science that is uniquely enabled by being on or near the Moon, including celestial and Earth observations.

Within this broad framework, the NLSI teams have the freedom to shift direction in response to changing scientific priorities and to take advantage of opportunities for new cross-team collaborations. The objective is to create a flexible, interactive institute that is responsive to both NASA's needs and to new scientific discovery. The individual team reports that follow this introduction illustrate the flexibility and creativity of this approach. Many further details are available at the NLSI website at lunarscience.nasa.gov.

Community Support. Following are examples of ways the NLSI as a whole has supported the lunar community and reached out to the public.

Lunar Science Website. The website lunarscience.nasa.gov is a dynamic repository of news about the Moon, with daily stories reflecting the wide current interest in the Moon. Other main sections include an overview of the NLSI, descriptions of current and planned lunar missions, summaries of EP/O activities, and a calendar of events (including the annual Lunar Science Forum). It also includes links to the individual websites maintained by each Team. The website has a readership in more than 150 countries around the world.

Lunar Science Forum. The NLSI has hosted, since 2008, the world's largest dedicated lunar conference in the form of an annual NASA Lunar Science Forum (LSF). The LSF features sessions relating to science "Of, On and From the Moon" in addition to exploration-centered initiatives, education, public outreach and commercial space ventures. The LSF is held at NASA Ames Research Center during the anniversary week of the Apollo 11 Moon landing. Attendance has exceeded 500 each year. The associated LunGradCon is a dedicated side-conference organized and attended solely by lunar science graduate students. This conference provides an opportunity for networking, sharing scientific results, and exposure of graduate students to senior leadership within the lunar scientific community. Additionally, the Next Gen Lunar Scientists and Engineers, a group of early career researchers, holds an annual workshop at the LSF that provides personal and professional development opportunities.

Shoemaker Prize. Each year, the NLSI presents the Gene Shoemaker Distinguished Lunar Scientist Award and associated keynote lecture at the Lunar Science Forum. This medal recognizes individuals who have significantly advanced lunar studies throughout their scientific careers. Past winners include Gene Shoemaker (posthumous), Don Wilhelms, Jeffrey Taylor and S. Ross Taylor.

Other Science Communities. The NLSI hosts several lunar "focus groups" that are open to all interested scientists. The current focus groups concentrate on Apollo Lunar Surface Experiments Package (ALSEP) data recovery, Lunar Space Biology and Astrobiology, Lunar Dust Atmosphere and Plasma, South Pole-Aitkin (SPA) Basin, Lunar Bombardment History, and Lunar Commerce. The NLSI regularly organizes sessions at professional meetings of the American Astronomical Society, the American Geophysical Union, the AAS Division for Planetary Science, the Lunar and Planetary Science Conference, the European Planetary Science Congress, and other organizations as time and funds permit. NLSI was a co-sponsor of the International Year of Astronomy. The NLSI also regularly presents on-line public lectures, often featuring scientists from NLSI teams, which are available to everyone through live video connections and archived podcasts.

Education and Public Outreach (E/PO). Each NLSI Team has its own E/PO coordinator and program, as described on respective team websites. NLSI Central coordinates a variety of outreach efforts. NLSI Central has supported Montana State University's "Geology of the Moon" on-line course for K-12 teachers, and sponsors the development of educational material for use by students and audiences with disabilities. One of the NLSI's most successful efforts was the development of a tactile guide to lunar geology for the blind with accompanying text in Braille. NLSI is pioneering high-profile public outreach and citizen science programs emphasizing inspiring students and the public. This includes International Observe the Moon Night, when tens of thousands of people around the world gather to view the Moon through telescopes and learn about our nearest neighbor in space. NLSI Central promotes campaigns with schools, amateur astronomers, and the Girl Scouts to enable observations of the Moon that directly support lunar research. Exploration Uplink, a project that allows students to remotely control a rover in a simulated lunar environment, has engaged over 10,000 students in sites as far away as South Africa and South Korea to participate in robotic exploration. The NLSI also works closely with the E/PO programs of the various NASA lunar missions including LCROSS, LRO, GRAIL, and Lunar Atmosphere and Dust Environment Explorer (LADEE) to present the public with an integrated view of NASA lunar science and exploration.

NLSI Central Staff. As a virtual institute, NLSI has a small central office at NASA Ames Research Center to oversee the operation of research teams distributed across the United States and around the world. The core administrative staff listed below form the organizational and collaborative hub for the domestic and international teams.

Yvonne Pendleton
Director

Greg Schmidt
Deputy Director

Doris Daou
Associate Director

David Morrison*
Senior Scientist, Founding Director

Brad Bailey
Staff Scientist

Shirley Berthold
Chief of Staff

Brian Day*
Director of Communication and Outreach

Joseph Minafra
Deputy Director of Communication and Outreach

Ricky Guest*
Collaborative Technologist

Teague Soderman
Senior Science Writer

Mark Friedenbach
Application Developer

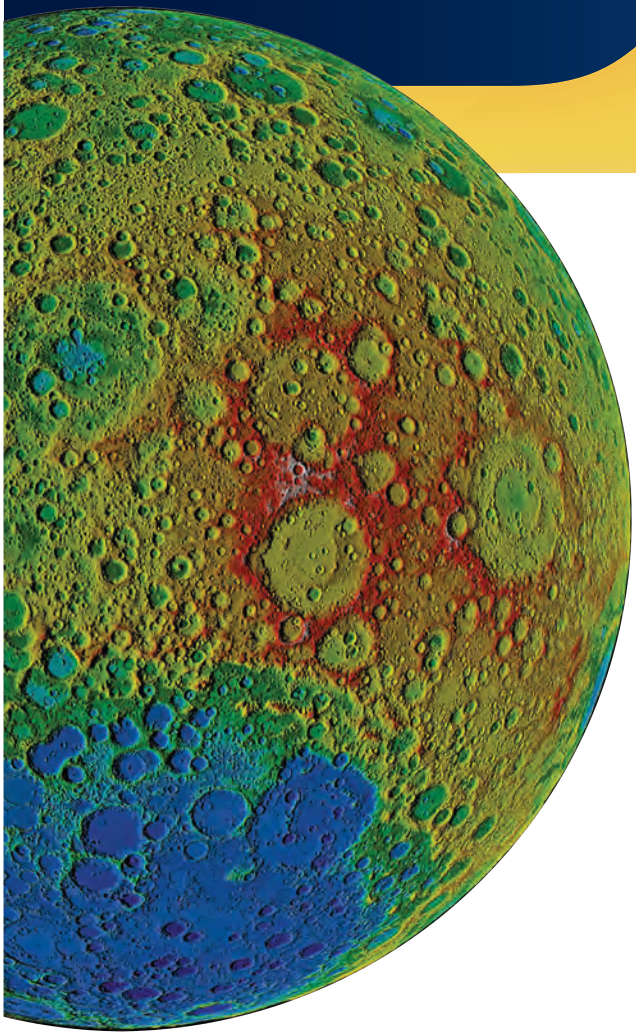
Jennifer Baer
Graphic Designer

Maria Leus
Executive Assistant (Intern)

Ashcon Nejad
Outreach (Intern)

** Shared resource with other programs*

Center for Lunar Origin and Evolution (CLOE)



Principal Investigator: William Bottke (SwRI)

Clark Chapman (Deputy PI)	Southwest Research Institute
Oleg Abramov	University of Colorado
F. Scott Anderson	Southwest Research Institute
Amy Barr	Southwest Research Institute
Robin Canup	Southwest Research Institute
Barbara Cohen	National Space Science and Technology Center
Luke Dones	Southwest Research Institute
Herbert Frey	NASA Goddard Space Flight Center
Erik Hauri	Carnegie Institution of Washington
David Kaufmann	Southwest Research Institute
David Kring	Lunar and Planetary Institute
Harold Levison	Southwest Research Institute
H. Jay Melosh	University of Arizona
Stephen Mojzsis	University of Colorado
Alessandro Morbidelli	CNRS-Observatoire de la Cote d'Azur
David Nesvorny	Southwest Research Institute
David O'Brien	Planetary Science Institute
Roger Phillips	Southwest Research Institute
Stephanie Shipp	Lunar and Planetary Institute
Timothy Swindle	University of Arizona
David Vokrouhlicky	Charles University, Prague
William Ward	Southwest Research Institute

Background. The National Research Council's 2007 Space Studies Board report identified three fundamental science concepts: (SB-A) lunar origin by giant impact, (SB-B) the existence of an early lunar magma ocean, and (SB-C) the potential of an impact cataclysm at 3.9 billion years ago (Ga), and listed the following themes that are directly relevant to the work described in this summary:

(1a) Test the cataclysm hypothesis by determining the spacing in time of the creation of lunar basins.

(1b) Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin.

(1c) Establish a precise absolute chronology.

(1d) Assess the recent impact flux.

In addition, the Decadal Survey report (NASA/NRC) organized the central questions of planetary science into three cross-cutting themes: building new worlds (understanding solar system beginnings), planetary habitats (searching for the requirements for life), and workings of solar systems (revealing planetary processes through time). Several of the central, guiding questions from these themes are described below:

(DS-A) What were the initial stages, conditions and processes of solar system formation and the nature of the interstellar matter that was incorporated?

(DS-B) How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?

(DS-C) What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?

(DS-D) What solar system bodies endanger and what mechanisms shield Earth's biosphere?

The Center for Lunar Origin and Evolution (CLOE), was specifically designed to address these critical questions. Our goals are (i) to use the Moon to tell us about the origin and history of the rest of the solar system, and (ii) to use the solar system to inform us on how the Moon formed and evolved.

Here we briefly describe CLOE's scientific research progress, highlighting the central questions that have been addressed by our work from 2009-2012.

Theme 1: Formation of the Moon. In exploring the implications of a giant impact origin of the Moon we address questions (SB-A), (DS-A), (DS-C), and determine the initial thermal state of the Moon, which informs (SB-B). The Giant Impact (GI) theory suggests that the Moon formed from debris ejected during a collision between a Mars-sized protoplanet and the early Earth. The GI theory is favored over other hypotheses because it provides a natural explanation for the Earth's initial rapid spin rate and the Moon's mass and low iron content. However, it has been unclear whether the GI theory can be reconciled with other key geochemical and geophysical traits of the Moon, including its close compositional similarity to the Earth's mantle, recent evidence for indigenous lunar water, and an initial Moon that was perhaps only partially molten when it formed.

Our approach constructs a self-consistent description of lunar origin via giant impact, starting with hydrodynamical models of the impact event itself, continuing with detailed thermodynamical, chemical and dynamical models of the evolution of an impact-produced protolunar disk, and concluding with direct simulations of the final assembly of the Moon and its associated thermal state.

We have performed the highest resolution simulations to date of Moon-forming impacts, and have conducted detailed comparisons between results from Lagrangian hydrocodes (SPH) and Eulerian hydrocodes (CTH) [Canup et al. 2012; Figure 1]. Both methods produce comparable results: an oblique, low-velocity impact of a Mars-size body with Earth can produce a massive protolunar disk and Earth's correct initial spin rate.

We have completed a new, generalized model for the thermodynamic state of the post-impact protolunar disk [Ward 2012]. This model provides a full description of a two-phase, vapor-magma silicate disk in hydrostatic and phase equilibrium, including radial temperature, pressure, and density profiles as a function of the disk's gas mass fraction.

The Moon has long been thought to be highly depleted in volatiles such as water, and published direct measurements of water in lunar volcanic glasses have never exceeded 50 parts per million. New analysis of lunar samples has shown, however, that water can be measured in particular lunar melt inclusions [Hauri et al. 2011]. The volatile contents are similar to primitive terrestrial mid-ocean ridge basalts and indicate the lunar interior may contain as much water as Earth's upper mantle.

We have developed a new model [Salmon & Canup 2012] showing how the Moon may have accumulated from an impact-generated disk in three phases. The inner disk was assumed to be a mixture of vapor and magma and was modeled to the Roche limit with a fluid treatment; outside the Roche limit, material can accumulate into the Moon, and we describe this region with a direct N-body accretion simulation. In phase 1, particles initially located beyond the Roche limit rapidly accrete until only a few massive bodies remain after a few months. The fluid disk is confined within the Roche limit by resonant interactions with outer bodies, which begin to recede away from the disk. In phase 2, resonant interactions weaken as the moonlets move away from the disk and the disk is freed to spread back out to the Roche limit over several tens of years. In phase 3, new moonlets are spawned from the inner disk and collide with the Moon to finalize its accretion in ~ 100 years. This longer formation timescale for the Moon is compatible with a partially molten Moon and with chemical equilibration between the disk and the planet.

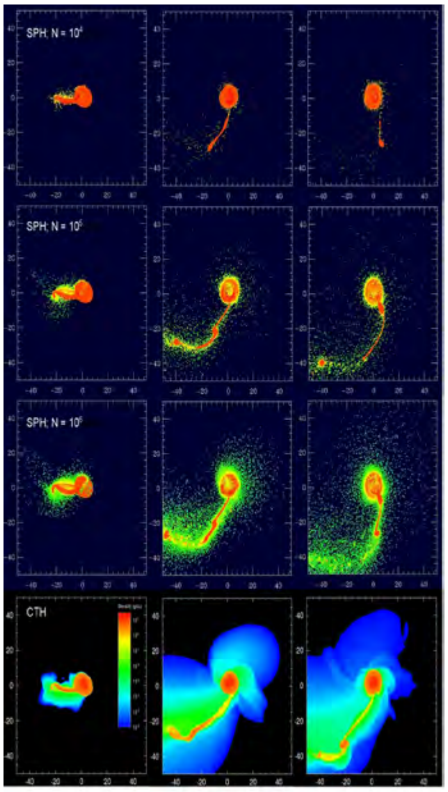


Figure 1. Simulation of a Moon-forming impact with SPH (top) and CTH (bottom). Frames show times at 5.4 hours after the impact of a 0.13 Earth-mass impactor. Color scales with the log of material density as shown in the color bar. From Canup et al. (2012).

As part of our attempt to model the Moon's temperature as it forms, we analyzed the melt produced as a function of impact properties using direct hydrodynamical simulations [Barr & Citron 2011], and developed a three-dimensional model of the Moon's temperature as it grew from a large number of accretionary impacts.

Theme 2: Observational Constraints on the Bombardment History of the Moon. We used inventive techniques to deduce new physical constraints on the lunar impact rate over the last 4.5 billion years, and we analyzed terrestrial, lunar and asteroid minerals that are sensitive to, and have information on, the record of ancient impacts on the Earth-Moon system (Theme 2a). After counting craters on a wide variety of lunar terrains, we have found evidence for the beginning of the lunar cataclysm on the Moon (Theme 2b). Our goal is to use lunar and meteoritic samples to establish an early lunar bombardment chronology. This work addresses key questions (SB-C), (DS-A), (DS-B), and (DS-C).

Theme 2a: Thermochronometry and the Bombardment History of the Moon. CLOE graduate student and postdoc research followed the following themes: (i) Impact processes in silicate crusts (Earth, Moon, asteroids); (ii) Bombardment record of the early Earth; and (iii) The thermal evolution of planetary surfaces from impacts and radionuclides. Highlights of our thermal-chemical studies of impacts include studies of samples from the Moon and Vesta.

For example, we investigated the thermal and temporal evolution of both Vesta and the Moon by comparative ultra-high resolution U-Th-Pb-Ti zircon depth profile analyses from the brecciated Millbillillie eucrite (Vesta) and four bulk Apollo 14 lunar samples. By searching for preserved 235-238U/207-206Pb ratios in different zircon domains (cores, mantles) within these individual crystals, we attempt to identify massive thermal events that affected them (i.e., bombardment). We are also implementing the Ti-in-zircon ([Ti]Zr) thermometer for precise estimates (independent of closure temperature (Tc)) of temperature in different mineral domains related to thermal disturbances.

We have shown the crystallization age of basalts from Vesta (eucrites) is well constrained at ~4.56 Ga by U-Pb and 207Pb/206Pb ages from eucritic zircons, whole rock 40Ar-39Ar ages of unbrecciated eucrites, and Hf-W data. Vesta has had intact basaltic crust from the first few years after the formation of the solar system's first solids. Subsequent thermal events recorded in the Millbillillie eucrites suggest that Vesta was likely hit by large impactors very early in its history (e.g., 4530 Ma). This age, ~40 Myr after initial solar system formation, statistically falls within range of proposed Hf-W model ages of the GI formation of the Moon 30-110 Myr after the formation of the first solids.

Lunar zircons we studied have 4.2-4.3 Ga ages. This is older than the pronounced clustering of crystallization ages in lunar impact-melt breccias at 3.9 Ga. Our work suggests that large, probably basin-scale impacts occurred on the Moon from 4.2-4.3 Ga. We conclude that the early bombardment of the Moon was probably made of waves, with one associated with the leftovers of terrestrial planet formation and a second one perhaps associated with the late migration of the giant planets.

Theme 2b: Relative Lunar Crater Chronology. We have analyzed the Moon's cratering impact record to better understand its bombardment history, from the later portions of the Late Heavy Bombardment until the present. We have compiled craters counts of Imbrium and Birkhoff basins from newly digitized Lunar Orbiter images, generating a new dataset of smaller craters within lunar basins. Primary results show that small crater size-frequency distributions (SFDs) of different areas of the Moon are dominated in different and unpredictable ways by secondary craters, and the shape of the SFD changed between the formation of Birkhoff (> 4 Gyr) and Imbrium (4 < age < 3.5 Gyr).

After the arrival of the LRO-WAC mosaic (March 2011), we began to compile size-frequency distributions (SFDs) of small craters (diameter, D < 10 km) superposed on the floors of numerous mid-sized (D = 80-100 km) craters at random locations and of various ages. About half of our initially selected mid-sized craters were compiled in the superposed crater SFDs dataset. From these data the absolute age of the floors have been computed using a model impact flux. Our work suggests most counted craters are primaries. The shape of the small crater SFD has also likely changed with time. Future work will model numerically how the impactor source is depleted over time to gain a better understanding of evolution of impactor populations. Finally, the range of our cumulative crater densities for crater floors is smaller than expected. A likely explanation for this is the impact rate for small lunar craters (D < 1 km) has declined more slowly than for the large ones.

In Marchi et al. [2012], we showed, using new counts of 15–150 km diameter craters on the most ancient lunar terrains, that craters found on or near the 860-km-diameter Nectaris basin appear to have been created by projectiles hitting twice as fast as those that made the oldest craters on various Pre-Nectarian-era terrains. This dramatic velocity increase is consistent with a late reconfiguration of giant planet orbits, which may have strongly modified the source of lunar impactors. It also suggests a starting time near the formation time of Nectaris basin. This possibility implies that South Pole-Aitken basin (SPA), the largest lunar basin and one of the oldest by superposition, was not created during the lunar cataclysm.

Theme 3: Determining Lunar Impact Rates. Once the surface of the Moon solidified, it mainly has been shaped by impacts. As a result, the surface of the Moon stands as a witness to the late stages of planet formation and the evolution of the planetary system as a whole. The goal of Theme 3, therefore, is to construct the most complete theoretical models of the impact history on the Moon based on new dynamical models of the Solar System. Here we address questions (SB-C), (DS-A), (DS-B) (DS-C), and (DS-D).

Theme 3a. Understanding Planet Formation in Order to Constrain the Moon's Earliest History. We have constructed the most advanced code to date to study the end-to-end process of planet formation, referred to as the Lagrangian Integrator for Planetary Accretion and Dynamics or LIPAD [Levison et al. 2012]. LIPAD's greatest strength is that it can accurately model the wholesale redistribution of planetesimals due to gravitational interaction with embryos, which has recently been shown to significantly affect the growth rate of planetary embryos. Initial LIPAD work shows significant differences with previous works. First, gaps open around the planets, stifling their growth. Also, the planetesimals collide with one another, effectively causing them to grind away and disperse. At the end of the simulation the system contains only 0.4 Earth-masses of material—too little to make the observed planets! We are currently varying free parameters, like the mass of the disk, to determine under what conditions this startling result can be reversed.

Minton & Levison [2012] addressed the formation of the terrestrial planets and the small mass of Mars. We find Mars is well explained by the addition of planetesimal-driven migration (PDM) to models of planetary embryo formation. Here Mars initially forms as one of several Moon-mass embryos inside of ~1AU. After the onset of PDM, the proto-Mars migrated to ~1.5 AU and gained most its full mass, leaving behind a wake of excited planetesimals between ~1-1.5 AU. The excited planetesimals collisionally grind and lose mass, leaving Mars isolated from late stage embryo-embryo mergers, which only occur inward of ~1 AU. This model has wide-ranging implications for not only the formation history of Mars, but also the distribution of small bodies left over from the epoch of terrestrial planet formation. Knowledge of how these remnant small body reservoirs are distributed will help understand the early bombardment history of the Moon.

We also probed the aftermath of the Moon's formation. Consider that core formation should have stripped the terrestrial, lunar, and martian mantles of highly siderophile elements (HSEs), which consist of gold, platinum, and other rare metals. Instead, each world has disparate, yet elevated HSE abundances. Late accretion may offer a solution, provided that ≥0.5% Earth masses of broadly chondritic planetesimals reach Earth's mantle and that ~10 and ~1200 times less mass goes to Mars and the Moon, respectively. Bottke et al. [2010] showed that leftover planetesimal populations dominated by massive projectiles can explain these additions, with our inferred size distribution matching those derived from the inner asteroid belt, ancient martian impact basins, and planetary accretion models. The largest late terrestrial impactors, at 2500 to 3000 km in diameter, potentially modified Earth's obliquity by ~10°, whereas those for the Moon, at ~250 to 300 km, may have delivered water to its mantle.

Theme 3b. Understanding Giant Planets Migration and the Late Heavy Bombardment. The Late Heavy Bombardment (LHB) is an epoch that is believed to have ended ~3.8 Ga with the formation of Orientale basin. The Nice model argues the LHB was set into motion by the rearrangement of the outer giant planets. We find the Nice model compelling because it quantitatively explains the orbits of the jovian planets and the capture of comets into several different small body reservoirs in the outer solar system (e.g., Trojans of Jupiter/Neptune, the Kuiper belt/scattered disk, the irregular satellites). These accomplishments are unique among models of outer solar system formation.

To further test the Nice model scenario, we conducted simulations to determine the evolution of giant planets (Nesvorny et al. 2010; Nesvorny 1011). We find that starting with 4 giant planets has low success in matching giant planet orbits and various other constraints. Our best results come from Solar Systems with 5 giant planets, with an ice giant ejected to interstellar space during the LHB. Thus, our work may suggest the starting conditions for the Solar System were very different than today.

The Nice model also affected the asteroid belt, with resonance sweeping by late giant planet migration potentially driving asteroids onto planet-crossing orbits. Minton & Malhotra [2011], calculated the eccentricity excitation of asteroids produced by the sweeping nu6 secular resonance during the epoch of giant planet migration. We found that the asteroid belt would not have survived if migration were too slow, < 4 AU/My. This migration rate is consistent with a subset of the Nice model. In cases where the asteroid belt survived, it was only depleted by roughly half—too small to account for all lunar basins.

Bottke et al. [2012] searched for evidence of the missing impactors. Many have assumed that the LHB ended across the solar system about 3.7 Ga with the formation of Orientale basin. Evidence for LHB-sized blasts on Earth, however, extend between 1.8-3.7 Ga in the form of impact spherule beds, globally-distributed ejecta layers created by Chicxulub-sized or larger cratering events. Using numerical simulations, we show most late impactors came from the "E-belt," an extended and now largely extinct portion of the asteroid belt between 1.7-2.1 AU. This region was destabilized by late giant planet migration. E-belt survivors now make up the high inclination Hungaria asteroids. Scaling from the observed Hungarias, we find E-belt projectiles made ~10 lunar basins between 3.7-4.1 Ga. They also produced ~15 Archean-era basins on Earth between 2.5-3.7 Ga, as well as ~70 and ~4 Chicxulub-sized or larger craters on the Earth and Moon, respectively, between 1.7-3.7 Ga. These rates are consistent with impact spherule beds and lunar crater constraints.

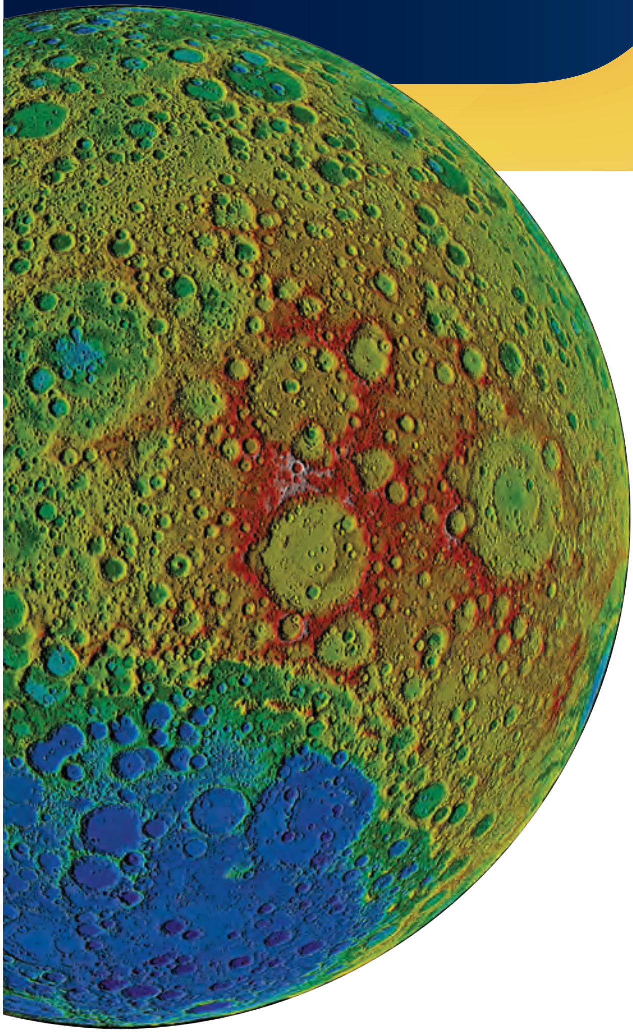
Community and Professional Development. CLOE is training the next generation of lunar scientists by actively fostering graduate-level education and post-graduate career development. For example, our recent graduates David Minton and Amy Barr became Asst. Prof. at Purdue and Brown, respectively. We currently have several postdocs: Julien Salmon & Channon Visscher work with Robin Canup on Theme 1, Michelle Kirchoff works with Clark Chapman on Theme 2, Kevin Walsh is working with Hal Levison on Theme 3, and Simone Marchi is working with William Bottke (and David Kring from CLSE) on Theme 3. Our team also includes graduate students from U. Colorado: Robert Citron completed his work with Amy Barr, Michelle Hopkins & Elizabeth Frank are continuing their work with Steve Mojzsis on Theme 2, and Kristin Sherman has completed her work with Clark Chapman on Theme 3.

We are also teaching classes at CU on the Moon. PI Bottke team-taught a graduate level class at the University of Colorado with fellow NLSI PI's Mihaly Horanyi and Jack Burns on Interdisciplinary Lunar Science (see http://lunar.colorado.edu/~jaburns/astr5835/). In addition, Co-I Mojzsis and postdoc Walsh have also been actively engaged in the teaching mission of CLOE, with a new graduate seminar class that was offered both in the Fall semester 2010 and Spring 2012 on the topic of Planetary Water and The Moon (a new graduate course offered in Planetary Sciences). Many CLOE members have given guest lectures. PI Bottke also combined forces with PI Kring (CLSE) to sponsor the Workshop on Early Solar System Bombardment I & II at the Lunar and Planetary Institute in Houston, TX.

Education and Public Outreach. CLOE has a cohesive E/PO program, led by Stephanie Shipp (E/PO Manager at LPI). Highlights include:

(a) In partnership with the Explore library program and six state library systems, the CLOE team created resources and provided training to support over 80 librarians in engaging their patrons in lunar science and exploration. (b) The CLOE Team partnered with the Summer Science Program (SSP) to develop and implement a two-day authentic research project based on CLOE science objectives that allows participation in NASA science activities, inspires interest in science and science careers, and enhances science skills.
(c) The CLOE website [http://cloe.boulder.swri.edu] is a portal to engage the public and increase their understanding of science that has been developed and maintained in partnership with high-school students (e.g., Denver School of Science and Technology; Denver North High School).

Lunar University Network for Astrophysics Research (LUNAR)



Principal Investigator:
Jack Burns (U. Colorado)

Joseph Lazio (Deputy PI)	Jet Propulsion Laboratory
Stuart Bale	University of California
Tim Bastian	National Radio Astronomy Observatory
Judd Bowman	California Institution of Technology
Richard Bradley	National Radio Astronomy Observatory
Chris Carilli	National Radio Astronomy Observatory
Douglas Currie	University of Maryland, College Park
Jeremy Darling	University of Colorado at Boulder
Douglas Duncan	University of Colorado at Boulder
Heino Falcke	ASTRON
Steven Furlanetto	Yale University
Lincoln Greenhill	Smithsonian Institution Astrophysical Observatory
Eric Hallman	Center for Astrophysics and Space Astronomy
Jacqueline Hewitt	MIT Kavli Inst. for Astrophysics & Space Research
Dayton Jones	Jet Propulsion Laboratory
Justin Kasper	Smithsonian Astrophysical Observatory
Chris Koehler	Colorado Space Grant Consortium
Abraham Loeb	Harvard University
Robert MacDowall	NASA Goddard Space Flight Center
Jan McGarry	NASA Goddard Space Flight Center
Stephen Merkowitz	NASA Goddard Space Flight Center
Andrei Mesinger	Princeton University
Thomas Murphy	University of California – San Diego
Susan Neff	NASA Goddard Space Flight Center
Kenneth Nordtvedt	Northwest Analysis
Jonathan Pritchard	Harvard - Smithsonian Center for Astrophysics
John Stocke	CASA University of Colorado
Gregory Taylor	University of New Mexico
Harley Thronson	NASA Goddard Space Flight Center
James Ulvestad	National Radio Astronomy Observatory
Eli Visbal	Harvard University
Benjamin Wandelt	University of Illinois at Urbana-Champaign
Kurt Weiler	Naval Research Laboratory
Penshu Yeh	NASA Goddard Space Flight Center
Thomas Zagwodzki	NASA Goddard Space Flight Center

NASA LUNAR SCIENCE INSTITUTE

The Lunar University Network for Astrophysics Research (LUNAR) is a team of researchers and students at leading universities, NASA centers, and federal research laboratories undertaking investigations aimed at using the Moon as a platform for space science. LUNAR research includes Lunar Interior Physics & Gravitation using Lunar Laser Ranging (LLR), Low Frequency Cosmology and Astrophysics (LFCA), Planetary Science and the Lunar Ionosphere, Radio Heliophysics, and Exploration Science. The LUNAR team is exploring technologies that are likely to have a dual purpose, serving both exploration and science. There is a certain degree of commonality in much of LUNAR's research. Specifically, the technology development for a lunar radio telescope involves elements from LFCA, Heliophysics, Exploration Science, and Planetary Science; similarly the drilling technology developed for LLR applies broadly to both Exploration and Lunar Science.

"A new Lunar Laser Ranging (LLR) program, if conducted as a low cost robotic mission or an add-on to a manned mission to the Moon, offers a promising and cost-effective way to test general relativity and other theories of gravity…The installation of new LLR retroreflectors to replace the 40 year old ones might provide such an opportunity." ***New Worlds, New Horizons in Astronomy & Astrophysics (NWNH)***

Lunar Laser Ranging. LUNAR has developed a concept for the next generation of Lunar Laser Ranging (LLR) retroreflector. To date, the use of the Apollo arrays continues to provide state-of-the-art science, over a lifetime of >40 yrs. This program has determined properties of the lunar interior, discovered the liquid core, which has now been confirmed by seismometry, and provided most of the best tests of General Relativity (GR). However, the single-shot ranging accuracy is now limited by the structure of the Apollo arrays. The next generation LLR program will provide lunar emplacements that will support an improvement in the ranging accuracy, and thus the lunar physics, by factors of 10-100.

In the near term, the LLR stations that have ranged to the Apollo retroreflectors will see an improvement in accuracy of 3-11 using their existing hardware. More important, the number of returns required to obtain a 1-mm normal point is reduced by a factor of 10-100. This means that as soon as the next generation retroreflectors are deployed, the improvements in the lunar and gravitational physics will begin.

"Deploying a global, long-lived network of geophysical instruments on the surface of the Moon to understand the nature and evolution of the lunar interior from the crust to the core…to determining the initial composition of the Moon and the Earth-Moon system, understanding early differentiation processes that occurred in the planets of the inner solar system." ***Vision and Voyages for Planetary Science in the Decade 2013-2022***

The LUNAR team has shown that the accumulation of dust on the lunar retroreflectors causes a significant loss in the return signal. Because of this, dust-mitigation techniques for use with corner cubes were studied. One such technique is to apply a hydrophobic surface coating. This coating, known as LOTUS, was originally developed to keep surfaces dust-free for missions to the Moon and Mars. The LOTUS coating is being applied to some of the corner cubes, and its far-field pattern is being studied to determine the effects of the coating on the corner cube.

Low Frequency Cosmology and Astrophysics (LFCA). The focus of the LUNAR LFCA research is to strengthen the science case and develop relevant technologies related to tracking the transition of the intergalactic medium (IGM) from a neutral to ionized state during the time that the first stars and first accreting black holes were forming using the redshifted 21-cm signal from neutral hydrogen. The eventual goal is to exploit the "radio-quiet" properties of the Moon's farside as the site for a lunar radio telescope to conduct these fundamental measurements.

The Astronomy and Astrophysics Decadal Survey (NWNH) identified "Cosmic Dawn" as one of the three objectives guiding the science program for this decade. In the science program articulated in NWNH (Chapter 2), Cosmic Dawn was identified as a science frontier discovery area that could provide the opportunity for "transformational comprehension, i.e., discovery." This is one of LUNAR's principal scientific thrusts.

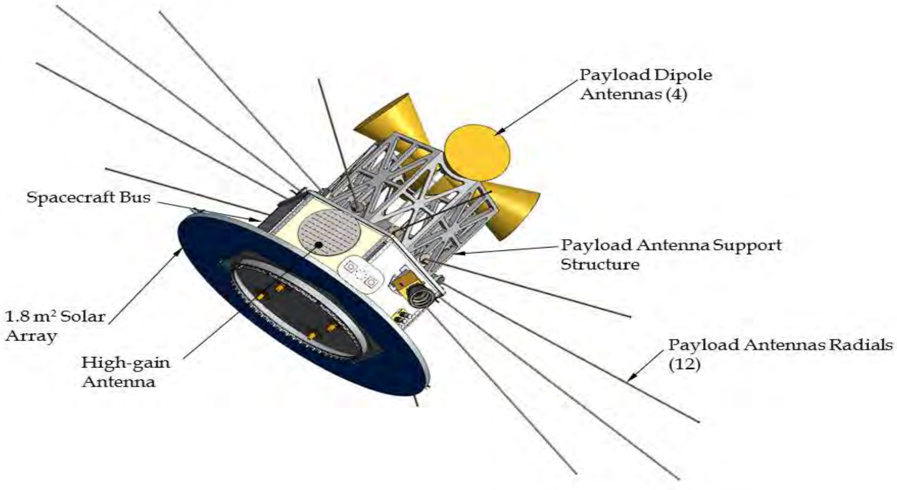


Figure 1. Artist's concept of DARE spacecraft.

LUNAR members have been pioneers in the development of the theory and numerical simulation of the first stars and galaxies, and predictions of sky-averaged spectrum and the spatial structure of the 21-cm signal. Concurrently, LUNAR has developed new technologies and mission concepts to observe the low frequency radio signals from Cosmic Dawn. One exciting advanced concept called DARE (Dark Ages Radio Explorer) will orbit the Moon, taking data only above the lunar farside, and will make the first observations of the first stars and galaxies at times <0.5 billion years after the Big Bang. In addition, LUNAR is engaged in technology development specifically to prove new antenna designs capable of being deployed in significant numbers on the lunar surface as an interferometric array. Innovative concepts include roll-out arrays of polyimide (e.g., Kapton) film with embedded metallic dipoles and magnetic helical antennas made of memory metals.

Although the primary focus of a future lunar radio telescope is likely to be Cosmic Dawn, such a telescope would be a powerful instrument for other high priority studies or would be able to conduct other interesting studies by virtue of the Cosmic Dawn observations. Examples include both searches for the magnetospheric emission from extrasolar planets and surveys for radio transients. These respond to recommendations from NWNH, which identified both "identification and characterization of nearby habitable exoplanets" and "time domain astronomy" as other science frontier discovery areas.

> "WHAT WERE THE FIRST OBJECTS TO LIGHT UP THE UNIVERSE AND WHEN DID THEY DO IT " ***NWNH***

Planetary Science connection to LFCA. The Scientific Context for the Exploration of the Moon (SCEM) identifies the "Lunar Environment," particularly the fact that the lunar atmosphere presents the nearest example of a surface boundary exosphere, as one of four guiding themes for science-based exploration. From this theme, the report develops a set of science goals, including "Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity." The SCEM report also notes that the Moon may continue to outgas and that the lunar atmosphere, as it is coupled to the solar wind, is a dynamic system. As such, long-term monitoring is required to understand its properties. Further, as a surface boundary exosphere, studies of the Moon are likely to inform processes occurring on Mercury, other moons, asteroids, and potentially even Kuiper Belt objects. LUNAR has developed a concept to measure the Moon's ionospheric density using the plasma frequency cutoff from observations with low frequency dipole antennas on the lunar surface.

Radio Heliophysics. High-energy particle acceleration occurs in diverse astrophysical environments including the Sun and other stars, supernovae, black holes, and quasars. A fundamental problem is understanding the mechanisms and sites of this acceleration, in particular the roles of shock waves and magnetic reconnection. Within the inner heliosphere, solar flares and shocks driven

> "Planetary exospheres…tenuous atmospheres that exist on many planetary bodies, including the Moon, Mercury, asteroids, and some of the satellites of the giant planets, are poorly understood at present. Insight into how they form, evolve, and interact with the space environment would greatly benefit from comparisons of such structures on a diversity of bodies."
> ***Vision & Voyages for Planetary Science in the Decade 2013–2022***

> "The Moon offers a large, stable surface in which to build a large, capable low-frequency radio array for the purpose of imaging solar sources at wavelengths that cannot be observed from the ground, an array that is well beyond the current state of the art for antennas in space." ***SCEM***

by coronal mass ejections (CMEs) are efficient particle accelerators which can be readily studied by remote observations. There remain significant questions to answer about these radio bursts and the acceleration processes that produce them, including where within the CME Type II emission is produced, and how the alignment between the shock surface and the coronal magnetic field changes the acceleration. Electron densities in the outer corona and inner heliosphere yield emission frequencies below ~10 MHz. Observations must be conducted from space because the terrestrial ionosphere is opaque in this frequency range, preventing any of this emission from reaching a receiver on Earth. Work on the Radio Observatory on the Lunar Surface for Solar Studies (ROLSS) concept has included refinement of instrument performance requirements, prototyping of critical components such as antennas and correlator electronics, and the use of simulations and observations from analogous instruments in space or radio arrays on Earth.

Since the first space exploration missions, in-situ interplanetary dust detection has been an important issue, both in order to understand the interplanetary and interstellar sources of dust, but also because of the effects that fast-moving dust can have on equipment and humans in space and on the lunar surface. Most dust measurements have been performed with instruments specifically designed to characterize dust particles, but recent work has shown that radio receivers are also able to measure electric signals associated with individual dust grains impacting spacecraft at high speed. Based on this recent work, the LUNAR team realized that the detection and monitoring of interplanetary dust could be a valuable additional science goal for ROLSS and any future far-side low frequency radio arrays. In order to learn more about this technique, and to demonstrate that ROLSS could also make such measurements, the LUNAR team investigated dust-related signals recorded by the S/WAVES radio instrument onboard the two STEREO spacecraft near 1 A.U. during the period 2007-2010.

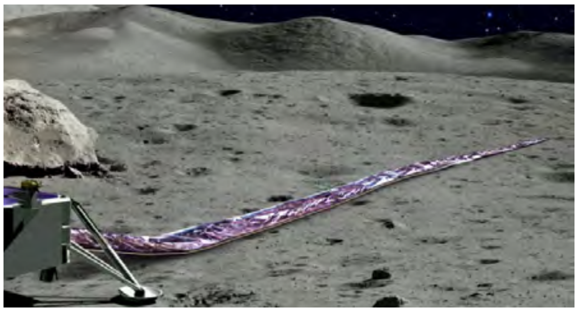


Figure 2. Artist's concept of a lander with a short length of polyimide film including two deposited dipole antennas (ROLSS prototype).

Exploration Science. The LUNAR team is investigating human missions to the lunar L2/Farside point that could be a proving ground for future expeditions to deep space while also overseeing scientifically important investigations. On an L2 mission, the astronauts would travel 15% farther from Earth than did the Apollo astronauts and spend almost three times longer in deep space. Such missions would validate the Orion Multi-Purpose Crew Vehicle's life support systems for shorter durations, would demonstrate the high-speed reentry capability needed for return from deep space, and would measure astronauts' radiation dose from cosmic rays and solar flares to verify that Orion provides sufficient protection. On such missions, the astronauts could teleoperate landers and rovers, which would obtain samples from the geologically interesting (and unexplored) farside (i.e., South Pole-Aitken Basin) and deploy a lunar radio telescope. Such telerobotic oversight would also demonstrate capability for future, more complex deep space missions.

The LUNAR Simulation Laboratory at U. Colorado has been developed to mimic the temperature and photon radiation environment of the Moon's surface over the course of a full lunar rotation. It has tested science equipment (e.g., polyimide film antennas) and deployment techniques using mini-rovers that are envisioned for both robotic and human exploration of the Moon. It serves as a facility to test other, Exploration-specific technologies, both for the Moon or other airless bodies such as NEOs.

> "The lunar surface offers extraordinarily radio-quiet sites on the lunar farside that could enable a highly sensitive low-frequency radio telescope… An innovative concept recently proposed would have a complete antenna line electrodeposited on a long strip of polyimide film…As a result of the high astronomical priority of this work and the uniquely enabling character of the radio-quiet farside lunar surface, such efforts deserve cultivation." ***SCEM***

Automated sensor deployment techniques are needed for surface missions in which instrument packages (either for Exploration or science) should or must be deployed at some distance from a lander. One option for deployment is a rover, but lower mass options, involving spring-and-pulley systems, are also being explored by the LUNAR team. Intended originally for lunar sensors, a spring-and-pulley system may be a useful technology for other low gravity environments.

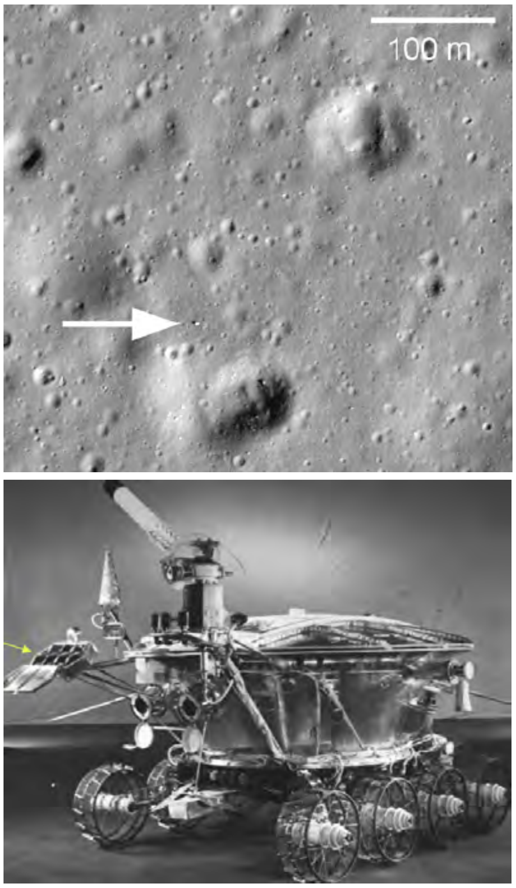


Figure 3. Top: LRO image of Lunokhod 1. Bottom: Lunokhod 1 lander.

An accurate grid or selenographic coordinate system will be critical in future robotic and/or manned missions. Lunokhod 1 had never been ranged to since the coordinates of the final resting place were not sufficiently accurate. Using the high resolution imagery, LRO identified the location of Lunokhod 1 and these coordinates were given to the LUNAR team for use at the Apache Point Observatory Station. This allowed laser returns to be obtained from Lunokhod 1 for the first time. However, the LLR position of Lunokhod 1 was different from the LRO coordinates by 100 meters. Thus, this new data point should allow a very significant upgrade to the seleodetic coordinate system being used by LRO. Additional retroreflectors will serve to tie down the coordinate system in a variety of new locations.

Drilling in the lunar regolith requires a different approach than used on Earth, as the Apollo astronauts discovered. Such drilling may be required either for stability or thermal control. The LUNAR team, with partner Honeybee Robotics, has been exploring a gas-assisted pneumatic drill, which is demonstrating relatively deep penetrations with limited resource requirements.

Regolith may prove to be an effective construction material. The LUNAR team has been exploring how modest equipment could be used to fuse lunar regolith into a concrete-like material, which could then be used for construction of large structures and astronomical telescope mirrors, without the expense of having to carry most of the material to the Moon.

Education & Public Outreach (E/PO). LUNAR has a diverse and aggressive E/PO effort aimed at enhancing the awareness and knowledge about the Earth-Moon system. The largest elements involve the creation of a nationally-distributed children's planetarium show and extensive teacher workshops, many in partnership of the Astronomical Society of the Pacific. Another key element is support for high school robotics clubs making their own models of a lunar rover capable of deploying a radio telescope on the lunar surface. A final strategy is to take advantage of NASA missions and natural events such as eclipses to increase public awareness of science and of NASA's role.

Figure 4. Students attend one of the planned public events.

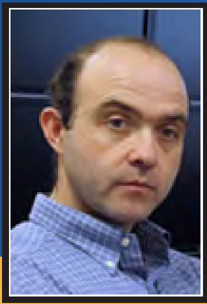
The children's planetarium program is based on the award-winning book "Max Goes to the Moon." NASA astronaut Alvin Drew played a role in the development of this show. On his mission to the ISS, he read the story "Max Goes to the Moon" to the children of Earth. Alvin introduces the story in our planetarium show. Using our well-developed process of "formative evaluation," we showed the program to test audiences of school children of the target age and also to hundreds of lunar scientists at the 2011 NLSI workshop. The feedback we gathered resulted in significant improvements to the show. "Max" is now complete and we are beginning distribution of the program.

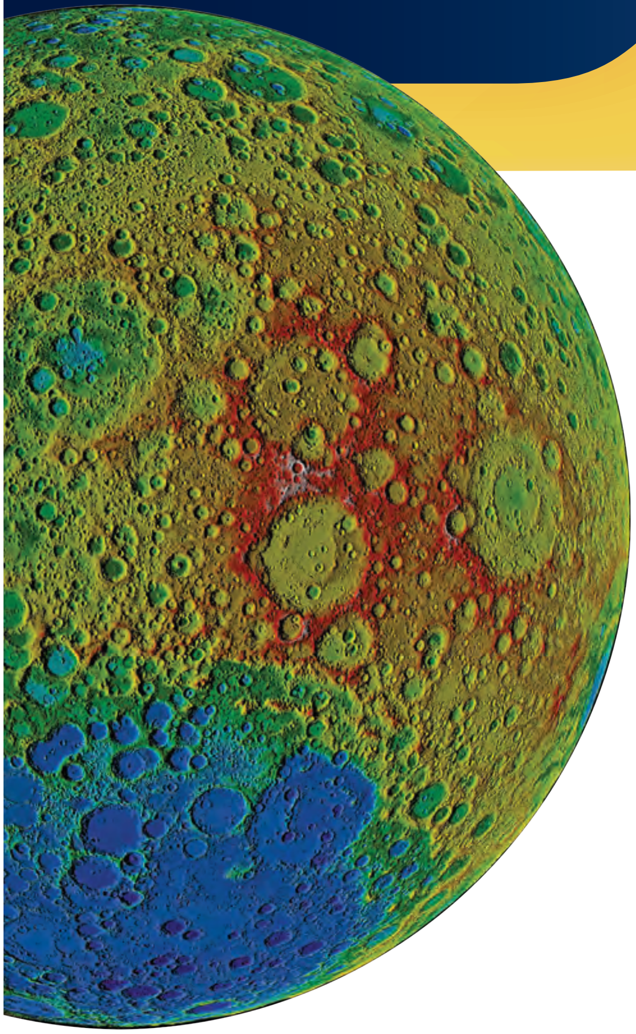
Our numerous K-12 teacher workshops focused on getting the latest discoveries about the Earth-Moon system and cosmology and the early Universe into the classroom. By holding workshops at the Astronomical Society of the Pacific meeting, we increased the number of teachers reached to much higher numbers than we originally proposed.

We began working with high school robotics clubs to challenge them to build a small rover that could deploy low frequency radio telescopes on the nearside and farside of the Moon. A student from one of these schools was invited to the NLSI Lunar Forum in the summer of 2011 to demonstrate his rover to the lunar community.

We planned public events associated with the LCROSS/LRO mission as well as the lunar eclipse in December 2010. The lunar eclipse was the largest public astronomy event in Boulder, CO since the "Deep Impact" comet mission in 2005. Approximately 1500 people crowded into a planetarium that seats 212 (using the lobby, the grounds, and the surrounding university). All heard about NASA's lunar science in addition to seeing the eclipse.

Science and Exploration of the Lunar Poles





Principal Investigator:
Ben Bussey (JHU/APL)

Jeffrey Plescia (Deputy PI)	Johns Hopkins University/Applied Physics Laboratory
Paul Spudis (Deputy PI)	Lunar and Planetary Institute
Vivake Asnani	NASA Glenn Research Center
Olivier Barnouin-Jha	Johns Hopkins University/Applied Physics Laboratory
Kerri Beisser	Johns Hopkins University/Applied Physics Laboratory
Phil Bland	Imperial College London
David Blewett	Johns Hopkins University/Applied Physics Laboratory
W. Carrier	Lunar Geotechnical Institute
Lynn Carter	NASA Goddard Space Flight Center
Dana Crider	Catholic University of America
Melinda Dyar	Mount Holyoke College
Richard Elphic	NASA Ames Research Center
Rebecca Ghent	University of Toronto
John Grant	Smithsonian Inst., Natl. Air and Space Museum
Mikhail Gubarev	Lunar and Planetary Institute
Charles Hibbitts	Johns Hopkins University/Applied Physics Laboratory
Mark Hopkins	U.S. Army Engineer Research and Development Center
Jerome Johnson	University of Alaska Fairbanks
Thomas Kaempfer	U.S. Army Engineer Research and Development Center
David Lawrence	Johns Hopkins U. Applied Physics Laboratory
Peter McCullough	Space Telescope Science Institute
Victoria Meadows	University of Washington
Richard Miller	University of Alabama in Huntsville
Thomas Orlando	Georgia Institute of Technology
Marc Postman	Space Telescope Science Institute
Brian Ramsey	NASA Marshall Space Flight Center
Mark Rosiek	United States Geological Survey
Soren-Aksel Sorensen	University College London
William Sparks	Space Telescope Science Institute
Elizabeth Turtle	Johns Hopkins University/Applied Physics Laboratory
R. Allen Wilkinson	NASA Glenn Research Center
Kris Zacny	Honeybee Robotics

NASA LUNAR SCIENCE INSTITUTE

Research by the JHU/APL Team is focused on the Moon's poles. When our team began this integrated research project, the lunar polar regions were regarded as "Luna incognita," the unknown Moon. During the last three years we have furthered our understanding of the polar regions so that they are now as well known, and in some case better known, than the rest of the Moon. "Luna incognita" has become "luna cognita."

Characterizing Luna Incognita:
• Study the geology of the poles • Characterize the surface and subsurface properties • Evaluate the ability to conduct surface operations, regolith excavation, and drilling • Evaluate potential instrumentation for science conducted from and on the Moon

The goal of our team is to advance our scientific understanding of the Moon's poles and to fill in strategic knowledge gaps that facilitate the robotic and human exploration of these areas. One aspect that could not have been predicted is the wealth of new data that have become available since we began. These new data produced by an armada of spacecraft, including India's Chandrayaan-1 and Japan's Kaguya mission as well as the NASA LRO and LCROSS missions, provide new insight into the processes and history of the lunar poles.

Collaboration has been a key aspect of our research. In addition to the natural collaboration between team members, our work has benefited by the successful collaboration with other NLSI teams as well as other US and international scientists and engineers.

Our research has addressed several high priority science concepts from the NRC Scientific Context for Exploration of the Moon (SCEM) report; "The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history," "The bombardment history of the inner solar system is uniquely revealed on the Moon," "The Moon is an accessible laboratory for studying the impact process on planetary scales," "Key planetary processes are manifested in the diversity of lunar crustal rocks," and "The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies." Additionally our work supports the goals of the Planetary Decadal Survey "What are the compositions, distributions, and sources of planetary polar deposits?"

Our research is divided into three themes: (1) Lunar Polar Environment, (2) Surface Characterization, and (3) Surface Science, Instrumentation, and Operations. By design, there is substantial overlap across topics, with each providing information to the others to facilitate a deeper, more thorough understanding of the questions that are posed.

1. Lunar Polar Environment. This theme includes: geology, illumination, volatile transport modeling, volatile-regolith laboratory studies.

Polar Geology. We have conducted several studies designed to elucidate the geological histories, nature and origin of the polar deposits. Using new spacecraft optical and radar images and Earth-based radar images, we have re-investigated and mapped the geology of the south pole, including a determination of the relative age of Shackleton crater. Shackleton was found to be more heavily cratered (older) than the mare surface at Apollo 15 (3.3 Ga), but less cratered (younger) than the Apollo 14 site (3.85 Ga). These data indicate that Shackleton is older than originally thought (Imbrian age) and may have collected extra-lunar volatile elements for at least the last 2 billion years. Such a history makes this crater an attractive site for exploration and possible human presence.

Lunar Polar Environment:
• Study the geology of the lunar poles • Characterize the polar illumination conditions • Migration, sequestration and stability of polar volatiles • Mechanisms of volatile storage

Polarimetric radar data acquired with the Mini-RF instruments indicate that ice may be abundant in the polar regions. Some craters show elevated CPR only

Figure 1. We have remapped the polar geology.

in their interiors; over 40 of these anomalous craters have been identified. The radar signature is consistent with the presence of ice deposits in the interior of these craters. Almost all are in permanent sun shadow and correlate with proposed locations of polar ice modeled on the basis of Lunar Prospector neutron data.

In response to the assertion by the Augustine Commission that a return to the Moon is unaffordable, we investigated a possible architecture that extends human reach beyond low Earth orbit by creating a permanent space transportation system with reusable and refuelable vehicles. Such a system is made possible by establishing a robotic outpost on the Moon that harvests water and produces propellant from the ice deposits of the permanently dark areas. This outpost can be established under existing and projected budgetary limitations within 16 years of program start.

Polar Illumination. The availability of high-resolution topography, combined with a high-fidelity simulation tool, has allowed polar illumination conditions to be well characterized, including data useful for planning future lander missions. We have developed a simulation tool called LunarShader that uses topography data and a user-selected Sun position to precisely determine which areas of the lunar surface are illuminated. Our first milestone was a comparison of Clementine images with simulations using Kaguya's laser-derived topography data. Comparison between our simulations and the actual images revealed a very good match. Now that we have validated the results from the simulation tool, we are able to map the illumination conditions at both poles, determining which areas receive the most sunlight, as well as mapping the areas of permanent shadow. We have continued to improve our knowledge of these areas by using the higher spatial resolution products that have been released be LRO's LOLA team. As the spatial resolution improves, we find that the areas that receive the most illumination get smaller. We are excited by future collaboration with the LROC team, combining our tool with their NAC high-resolution analyses.

Part of our research has considered the affect of placing solar arrays on different mast heights. We have found that even mast heights of a few meters can result in increased Sun visibility compared with the surface illumination.

Polar Volatiles. Since our team was established, volatiles in polar regions have been definitively detected. We have analyzed data regarding lunar volatiles and conducted modeling to support interpretation of the data. This work includes atmospheric modeling to consider the roles of volatile transport and space weathering.

The impact of the Lunar Crater Observation and Sensing Satellite (LCROSS) into the crater Cabeus released water and other volatiles into space, where they were observed by LRO, LCROSS, HST, and ground-based telescopes. We modeled the propagation of the vapor release and compared that to the observed light-curves for H_2O, OH, H, O, Na, H_2, CO, Mg, Ca, and Hg. For selected species, we determined the timing, temperature, bulk velocity, mass, and regolith abundance of the species. This study was not included in our original NLSI proposal, but arose from the interactions among our NLSI team members and the NSLI DREAM team after the success

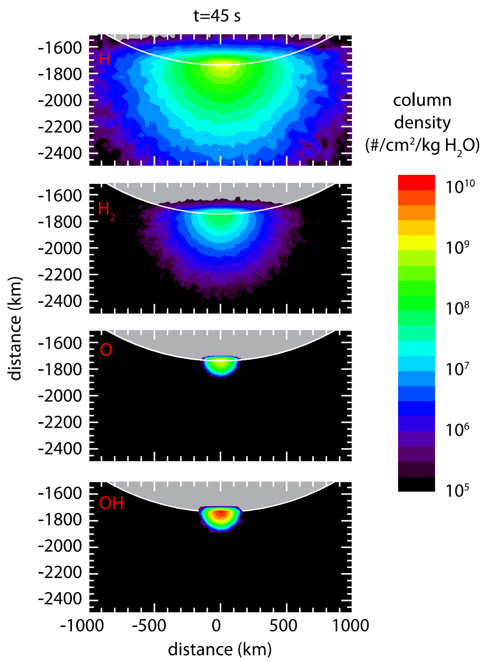


Figure 2. Modeled photodissociated products of water in the LCROSS plume.

of the LCROSS experiment. We used two-dimensional modeling of space weathering processes on the Moon to provide a framework for interpreting spacecraft data regarding polar volatiles. We have simulated the evolution of an ice layer over time and compared the model results as they would be observed in neutrons, FUV, radar, and in situ. This work enables a self-consistent interpretation of the seemingly disparate data on the distribution and abundance of volatiles in lunar polar regions coming from LRO, LCROSS, and Chandrayaan-1.

Volatile-Regolith Modeling: Our team is conducting laboratory and modeling experiments to better characterize and understand the nature and evolution of H_2O, hydroxyl, and other volatiles potentially at the poles. We are conducting Temperature Programed Desorption measurements on lunar analog materials to determine the thermal stability of both molecular water and hydroxyl on the surface. We also characterize these adsorbed species with UV through IR reflectance measurements under appropriate pressure and temperatures.

We have identified a compositional dependence in the thermal stability of water on lunar analog materials. When that data is coupled to our models of water evolution, it affects our prediction of the distribution of water (and hydroxyl) on the Moon. Additionally, by experimentally and theoretically investigating the stability, formation, and loss of water and hydroxyl, we can understand better if and how solar wind may form hydroxyl and how this hydroxyl may evolve to form water. Our experiments to determine the spectral nature of adsorbed water and hydroxyl enable us to assign the infrared absorption bands observed on the Moon to water or hydroxyl, thus providing insight into the origin and nature of these materials.

2. Surface Characterization. We have been using the latest data to study lunar surface characteristics. We have determined that self-secondary cratering on the continuous ejecta is a significant factor during an impact event. Such self-secondary craters are in part buried by melt and bouldery ejecta facies indicating that they formed concurrently with ejecta emplacement. Since the lunar chronology is tied to the crater frequencies on the Copernicus and Tycho ejecta blankets, if those frequencies do not represent the impact flux, the chronology will be incorrect.

We have also discovered that impact melt can occur in simple highlands craters down to diameters as small as 170 m. These craters have been interpreted as due to vertical impacts where maximum shock and heating occur (compared with more oblique impacts). As vertical impacts are relatively rare, so are such small craters with impact melt.

We have been examining the mineralogical composition and thermal history of low-calcium pyroxenes excavated from deep within the lunar crust. The composition and stratigraphy of these rocks provide key constraints on the nature and evolution of the lunar magma ocean. We have also been mapping the distribution of hydroxyl absorptions across the Moon, likely produced by solar wind bombardment of the lunar regolith. The OH- production hypothesis is being tested by characterizing the volatile distribution on localized scales at different times in the Lunar day, to evaluate whether it is transient or stably distributed.

3. Surface Science, Instrumentation, and Operations. This theme consisted of diverse objectives with the common thread that they either uniquely use the lunar poles or are enabled by a lunar polar location.

Excavation & Mobility Modeling. The goal is to develop physically based discrete element method (DEM) models of excavation and mobility problems on the Moon. The effects of different gravity, soil types and physical processes on the Moon, asteroids, and other planets make it impossible to accurately predict machine performance from Earth-based tests alone. We have: (1) conducted physical testing of wheel digging, static and percussive excavation, penetration, and geotechnical tri-axial strength tests on lunar simulants (primarily JSC-1a); (2) developed DEM model capabilities; (3) validated model capabilities by simulating physical tests using the models. Our most significant

Surface Science, Instrumentation & Operations:
• Mobility & Excavation Studies
• Use of Ground Penetrating Radar
• Neutron Studies
• Earth Observation

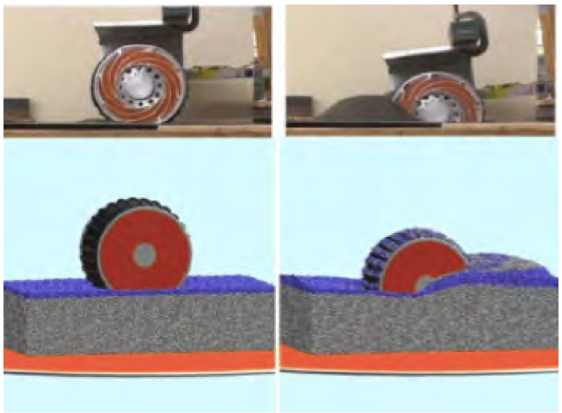


Figure 3. We compare physical testing with modeling results.

achievement is the development and validation of a physical DEM and distribution of its beta version to Glenn Research Center and CRREL for testing and use in simulating physical tests. While the DEM was developed for excavation and mobility applications, its design is sufficiently general that it can be applied to other important lunar and small body problems, such as volatile migration in lunar regolith, and asteroid properties. Other accomplishments include developing extensive physical test data related to excavation and mobility and lunar simulant mechanical properties.

Ground Penetrating Radar. Ground-Penetrating Radar (GPR) data from terrestrial analog environments can help constrain models of the evolution of the lunar surface, help predict the nature of subsurface properties, and aid in interpretation of orbital SAR data. GPR data from terrestrial settings can constrain the range of expected radar properties associated with varying substrates, thereby providing a tool for predicting the physical properties, clast-size distribution, and layering of the lunar subsurface. The goal of our work has been to demonstrate the capabilities of GPR in defining the range of radar properties at terrestrial sites where geologic processes, settings, and/or materials may be similar to those encountered on the Moon. Fieldwork has been conducted at five planetary analogue sites; Meteor Crater, Sunset Crater and SP Cone, the Columbia River Plateau basalts, and multiple locations on the Big Island of Hawaii.

By comparing analysis of GPR with the known local stratigraphy, we have shown that GPR can be used to probe the subsurface and help constrain the physical properties and setting of near surface materials. Our work highlights the utility and portability of using such a GPR during future exploration on the lunar surface to map geologic environments and target locations for sampling and suitable for eventual human exploration.

Neutron Studies. We have focused on: 1) Determining the feasibility of making high spatial resolution neutron measurements on the surface; and 2) Carrying out neutron transport modeling and data analysis to test ideas about measuring lunar hydrogen abundances. We studied the design of a surface high-resolution neutron imager using two different technologies, collimated and grazing incidence. Our analysis shows that a collimated instrument is required to collect such measurements.

Recent spectral data have shown the presence of surficial water over large expanses of the lunar surface. These results have led to a reexamination of the hydrogen abundance sensitivity limits of orbital neutron data. A wet-over-dry, two-layer stratigraphy has been modeled for the first time using neutron transport codes. Application of this effort to Goldschmidt crater reveals that it may have an enhanced hydrogen content of 0.1-1% water equivalent hydrogen. We have also studied data from the Lunar Exploration Neutron Detector (LEND) in order to better understand how these data provide information of lunar surface hydrogen abundances. We have confirmed that the LEND instrument is sensitive to lunar surface compositional variations from both the collimated and uncollimated sensors.

Earth Observation. Our goal is to examine the potential for a long-term full-disk Earth observing instrument on the Moon. The intent is to develop an instrument concept to characterize the remotely detectable physical and biological signatures of the Earth as a function of time. A lunar polar vantage point is unique, making it possible to track Earth's ever-changing photometric, spectral and polarimetric signatures in a manner analogous to future observations of terrestrial planets orbiting other stars.

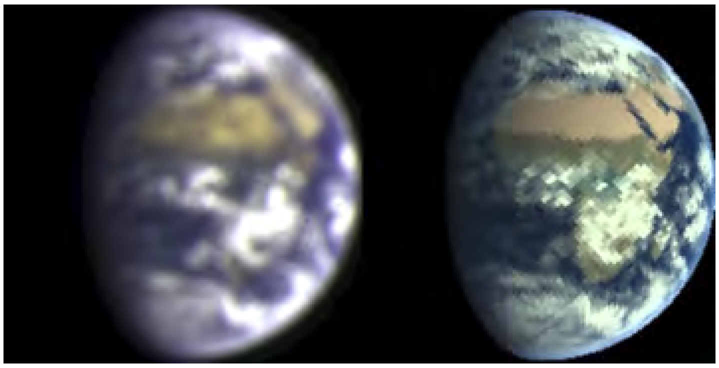


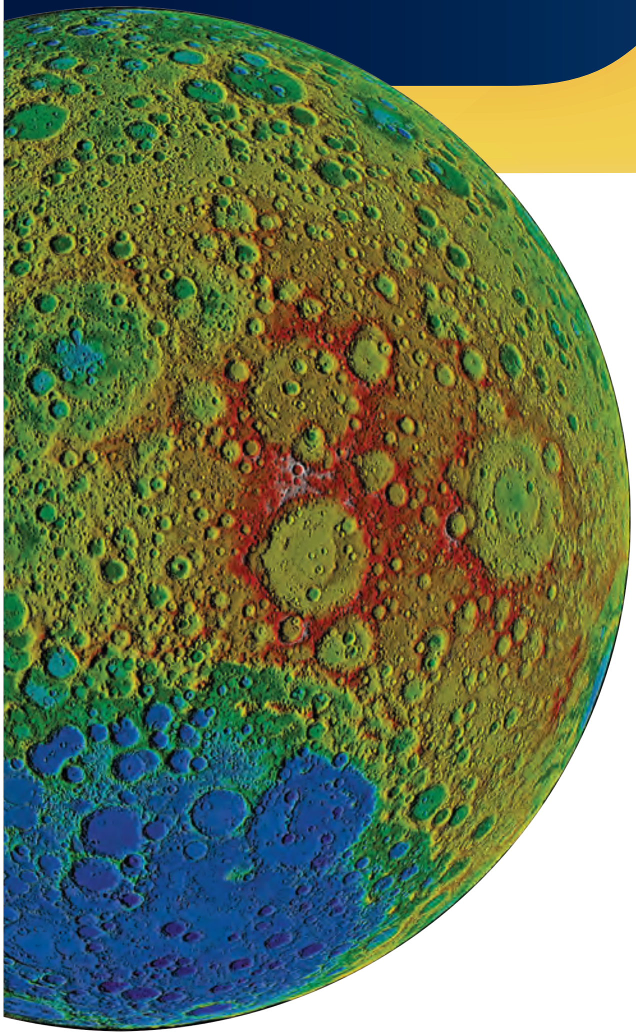
Figure 4. Comparison between LCROSS observations and model results.

The work includes the appearance and spectroscopic signatures and polarizations of the Earth and the strength of circular polarization signatures from biological material. Though not part of the original proposal, we fostered a collaboration with the LCROSS team to utilize their spectroscopy and imaging (UV to mid-IR) of the Earth at three very different orientations and phases. Sophisticated and detailed models have been produced by the NASA Astrobiology Institute Virtual Planetary laboratory for the Earth covering the three LCROSS Earth observing epochs. We find a good correlation between the actual and modeled results.

Education & Public Outreach. Conveying the excitement of studying the Moon to the general public is an important aspect of our work. The E/PO effort for our NLSI team continued to promote lunar science education through formal education and public outreach activities. Formal education activities included middle and high school educator professional development and a higher education lecture series. For Public Outreach, NLSI collaborated with the Maryland Science Center to host an event for International Observe the Moon Night. Also we maintain a website that reviews current lunar research done by NLSI and video archives of NLSI lecturers (http://lunarpoles.jhuapl.edu/).

The "Unknown Moon Institute" workshops are a professional development opportunity for middle and high school educators from around the country. During this five day workshop, teachers receive in-depth content and participated in rich inquiry-based activities about lunar science. As part of our E/PO effort we have developed a Lunar Geology Map lesson (that has passed SMD Product Review) that presents a discussion of types of geologic features found on the Moon.

Dynamic Response of the Environment at the Moon (DREAM)



Principal Investigator: William Farrell (GSFC)

Greg Delory (Deputy PI)	University of California
Rosemary Killen (Deputy PI)	NASA Goddard Space Flight Center
Stuart Bale	University of California
Lora Bleacher	Science Systems and Applications, Inc.
Tony Colaprete	NASA Ames Research Center
Michael Collier	NASA Goddard Space Flight Center
Rick Elphic	NASA Ames Research Center
Dave Glenar	New Mexico State University
Nick Gross	Boston University
Jasper Halekas	University of California
Richard Hartle	NASA Goddard Space Flight Center
Michael Hesse	NASA Goddard Space Flight Center
Richard Hodges	University of Colorado
Dana Hurley	Applied Physics Laboratory
Telana Jackson	NASA Goddard Space Flight Center
John Keller	NASA Goddard Space Flight Center
Dietmar Krauss-Varban	University of California
Robert Lin	University of California
John Marshall	SETI Institute
William Patterson	NASA Goddard Space Flight Center
Menelaos Sarantos	University of Maryland – Baltimore County
Harlan Spence	University of New Hampshire
Timothy Stubbs	University of Maryland – Baltimore County
Richard Vondrak	NASA Goddard Space Flight Center
Heather Weir	Science Systems and Applications, Inc.

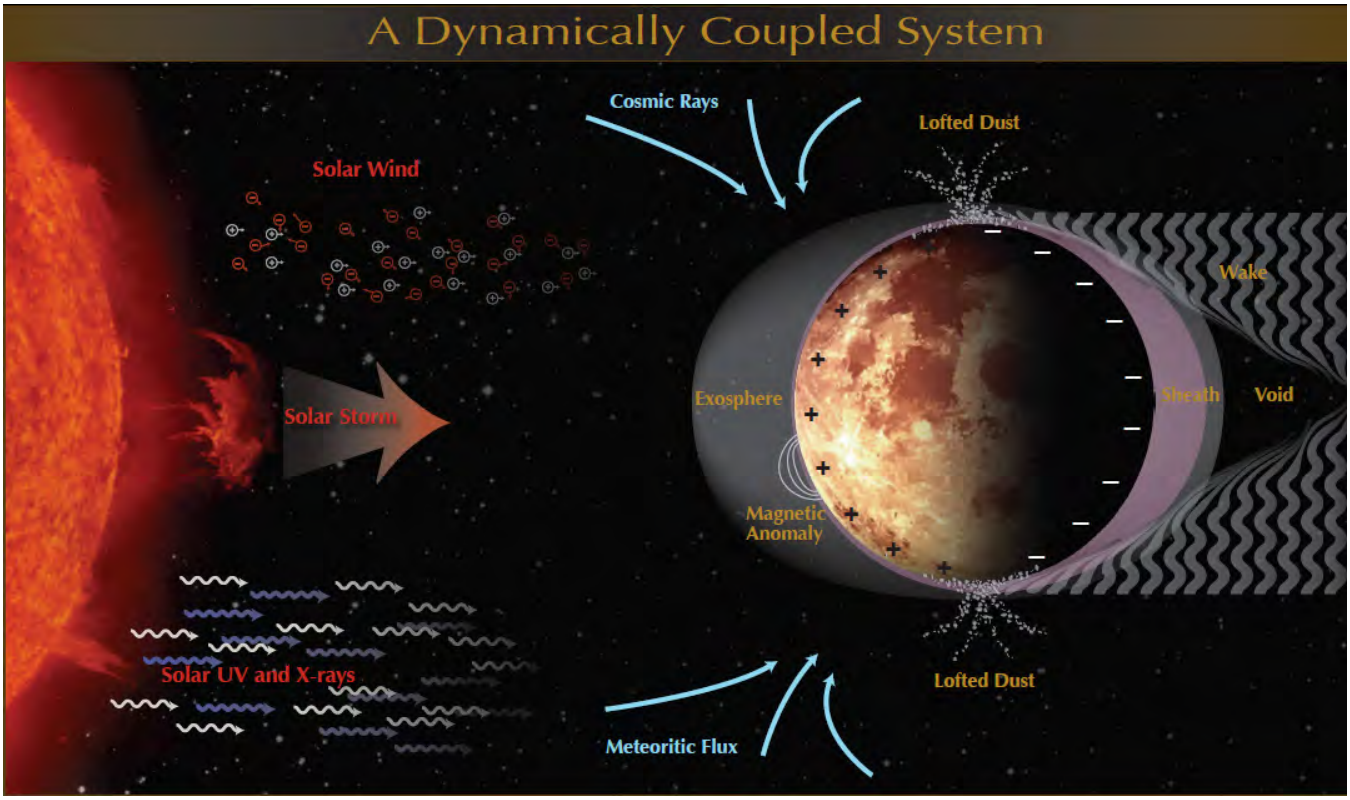


Figure 1. The solar-lunar connection studied by the DREAM lunar environment center.

While the Moon is often considered a stagnant "dead" body, it actually percolates with activity at the submicron and atomic levels; this activity animated by incoming solar energy and matter. In fact, the oxide-rich interface is in constant interaction with its environment, acting as an obstacle to inflowing solar plasma and continually releasing solar-stimulated atomic neutrals. These interactions create a super-surface layering about the Moon containing (1) a plasma interaction region that includes a near-surface plasma sheath and an extended, trailing solar wind plasma wake and (2) a neutral surface boundary exosphere and exo-ionosphere that extends hundreds of miles above the surface (see Figure 1). Apollo-era studies of these two systems revealed their presence and the tantalizing possibility of a complicated and dynamic neutral-ion-volatile-plasma-dust environment.

NASA's Lunar Science Institute (NLSI) team called "Dynamic Response of the Environment At the Moon (DREAM)" is a lunar environment center consists of 12 expert partners embarking on an advanced study of the surface-gas-plasma environmental systems at the Moon. The team especially examines how solar energy and matter affects the lunar surface (including the effect on surficial water, OH, Na, and other sequestered species), and in the understanding of the response of the surface to this solar energy input. DREAM's theory-modeling-data validation efforts explore the common linkages between plasma-neutral-surface system and to understand the system response during environmentally-extreme events like a passing solar storm or moderate sized, high velocity impact. DREAM E/PO has a primary focus on advancing the teacher and student understanding of lunar extreme environmental conditions (i.e., the Lunar Extreme Program), such as the lunar surface reaction to solar-created coronal mass ejection and impacts/gas releases.

The DREAM lunar environment center addresses the fundamental question: "How does the highly-variable solar energy and matter incident at the surface interface affect the dynamics of lunar volatiles, ionosphere, plasma, and dust?" To answer this, DREAM has formulated four primary science objectives:

1. Advance understanding of the surface release and loss of the neutral gas exosphere over small to large spatial scales and a broad range of driver intensities.

2. Advance understanding of the enveloping plasma interaction region over small to large spatial scales and over a broad range of driver intensities.

3. Identify common links between the neutral and plasma systems and test these linkages by modeling extreme environmental events.

4. Apply this new-found environmental knowledge to guide decision-making for future missions, assess the Moon as an observational platform, and aid in human exploration.

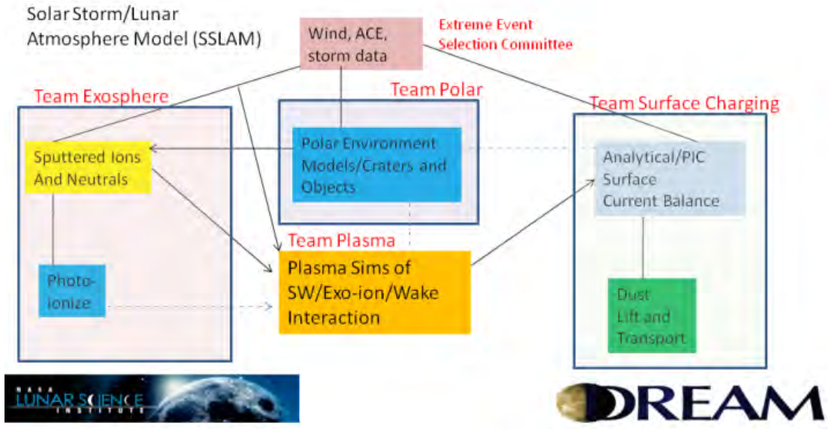


Figure 2. Layout of the DREAM models used in the Solar Storm/Lunar Atmosphere Modeling (SSLAM) effort.

In the first three year of DREAM, a number of key advancements and discoveries were made in each of these objectives. However, one of the most substantial and lasting contributions of the center is the integrated Solar Storm/Lunar Atmosphere Modeling (SSLAM) effort, where DREAM models were run in sequence to predict the behavior of a passing dense, heavy coronal mass ejection (CME) of plasma at the Moon. This modeling effort of the storm phenomenon was initiated in late 2009 and was capped by a week-long intramural workshop in mid-year 2011 where cross-connected model results were presented and dissected. In essence, the SSLAM effort was the completion of a key element of objective #3, where common links between the plasma, surface, and exosphere were examined in a period of extreme space weather, at time period when existing links are accentuated by in the extreme plasma environment. While it is well-known that solar storms have an effect in the Earth's magnetic field and ionosphere (i.e., they are 'geo-effective'), solar storm effects at the Moon have not been previously examined.

Figure 2 shows the layout of SSLAM. An extreme event selection committee identified an ideal event for study: the intense Earth-directed CME in early May 1998. Plasma and radiation measurements from upstream monitors like ACE and WIND were then used as inputs to models of the lunar exosphere, polar environment, surface charging, and lunar surface-plasma interaction. Key finds include the following: 1) During a CME passage, the exposed lunar surface receives an increase in mass flux from the exogenic CME driver plasma of about 300 tons. 2) However, this same intense driver plasma containing large concentrations of heavy multi-charged ions can liberate atoms from the regolith via sputtering, releasing 100-200 tons of atomic/molecular material over the 2-day CME passage. 3) The lunar exosphere is thus expected to become enhanced or 'bulked up' during a CME passage due to sputtering (see Figure 3). 4) Sputtered ions also populate the near-Moon environment, and there is a general increase in CME plasma ions reflected upstream - the combination acting to slow down the driver plasma. 5) Anomalous surface charging effects occurred, including the release of originally-trapped dayside photo-electrons (due to a reduction in the trapping surface potential) and anomalous ion inflows into polar craters with local sputtering acting as a source of volatile loss.

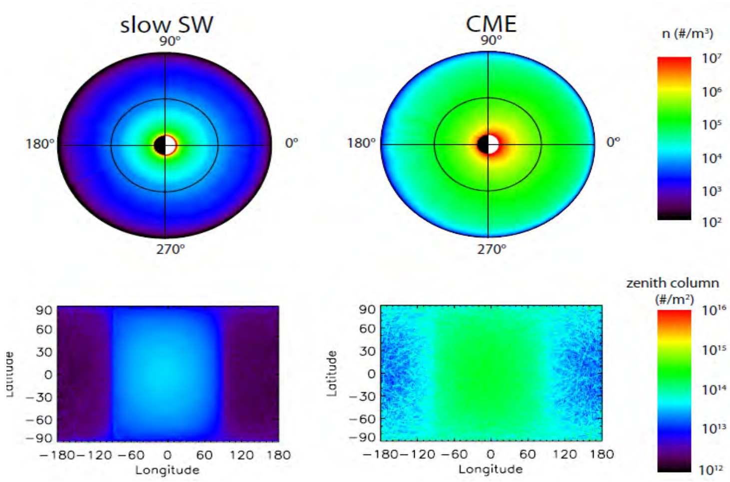


Figure 3. The enhancement in the sodium exosphere from CME sputtering (from Killen et al. 2012).

This SSLAM effort cross-integrates individual DREAM models to form a larger system-level model of the environment. Such an overarching endeavor involving over 30 people and integrating 10 independent models could simply not be constructed via a single or even multiple LASER awards – it truly requires an institute formed with the proper personnel, data, and modeling tools to perform the job.

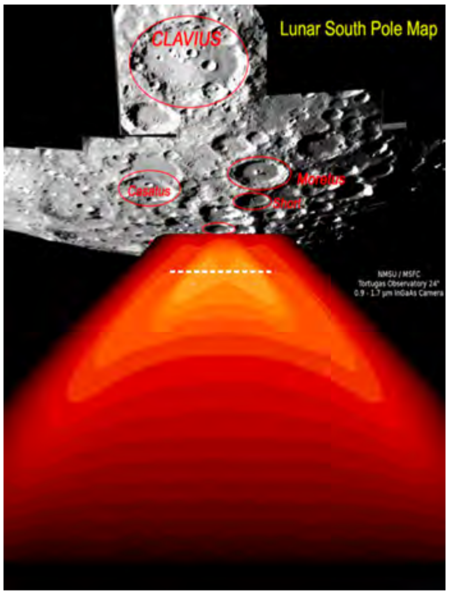


Figure 4. A model of the LCROSS sodium plume (Killen et al., 2010).

The SSLAM effort was a focal point of DREAM E/PO activity. Two high schools, Eleanor Roosevelt in Greenbelt MD and Seton-Keough in Baltimore MD, had students participate the DREAM's Lunar Extreme Program: a 16-week online class and webinar series featuring a set of teaching exercises and lectures on solar/space weather at the Moon (see syllabus at http://ssed.gsfc.nasa.gov/dream/DREAM/syllabus1.html). This program culminated in student participation in the DREAM SSLAM workshop in June 2011.

Another key advancement made by DREAM team members and shared with our sister institution, the Colorado Center for Lunar Dust and Atmosphere Science (CCLDAS), is the discovery of a precursor plasma layer ahead of the Moon. Prior to the NLSI, the conventional wisdom was that the solar wind ions and electrons incident directly on the dayside lunar surface were complete absorbed by the surface, leaving a trailing void in the flow behind the Moon (i.e., commonly called the lunar wake). From a philosophical perspective, the lack of a lunar precursor layer has been considered troubling since objects in a flowing plasma naturally tend to transmit upstream information (i.e., plasma waves) into the flow.

However, Andrew Poppe, performing his graduate work under CCLDAS (at the University of Colorado), developed a set of provocative plasma simulations of the dayside plasma sheath region that clearly showed the development of a new electrostatic layer lying at heights above the dayside photo-electron sheath. This layer had the ability to both reflect incoming solar wind electrons and accelerate some of the cold photoelectrons outward from the Moon. Simultaneously, DREAM Co-I Jasper Halekas of UC Berkeley was reporting the detection of unusual beams and anomalous reflected electron distribution from the Lunar Prospector MAG/ER instrument. The two recognized that each had a key piece of information and started a strong collaboration with Poppe eventually becoming a DREAM post-doc at UC Berkeley. Since that time, they have confirmed the presence of a lunar plasma precursor layer using ARTEMIS observations (in one case detected > 8000 km from the Moon). The plasma layer is similar in nature to the terrestrial foreshock region ahead of the Earth's bow shock and is a source of plasma turbulence that is attempting to slow/alter the incoming solar wind electron population. Indeed, the Moon does transmit information into the upstream plasma; this to indicate its presence and to divert & slow the incoming fast solar inflow.

While the advances above demonstrate the team's large-scale coherent modeling efforts and center-to-center collaborations, a third DREAM advance demonstrates the team's innate ability to immediately respond to new events. Specifically, DREAM Co-I Rosemary Killen was able to obtain time on the Kitt Peak Telescope to observe the 2009 LCROSS impact with the sensitive 589-nm sodium D-line filter. Unfortunately, the initial opportunity lacked funding for both investigator labor time and travel. However, DREAM resources, in the form of a block grant located at GSFC, could be easily redirected to fully exploit this unplanned opportunity. In fact, to solicit support from HQ was simply not possible: the submission of a LASER proposal would have been reviewed and awarded long after the LCROSS encounter. This investigation in particular highlights a clear advantage of an institute-type award: resources are more easily accessible and available to the working 'boots-on-the-ground' scientists.

The observation campaign occurred during clear skies and was very fruitful, providing the only ground-based observation of the LCROSS impact. In fact, impact-ejected sodium from the bottom of Cabeus crater was observed to diffuse for up to 9 minutes after the impact. Comparing Monte Carlo models of the Na

Figure 5. DREAM's Mike Collier at Maryland Day.

release (like Figure 4) to the telescopic observations suggest that the impact temperature for the species was near 1000K. This information provided critical and independent support to the LCROSS team who also arrived at a similar temperature.

DREAM topics tie into many of the cross-cutting themes defined in the "Vision and Voyages" Planetary Decadal study [Nat. Acad. Press, 2011]. The DREAM lunar environment center emphasizes the variable solar-lunar chemical and physical surface processes, and thus connects directly to the "Working of the Solar System" Theme #9 [Planetary Atmospheres] and #10 [Basic Chemical and Physical Processes]. However, DREAM's emphasis on volatile migration and solar wind/surface interactions also ties it to the "Building New Worlds: Theme #3 [Supply of Water] and Planetary Habitats Theme #4 [Modern Organic Synthesis]. A key Decadal theme is the role of water and organics in the building of new worlds. In 2009, LCROSS and Chandrayuan-1 M3 observations indicate that the Moon harbors and possibly actively transports water and OH. DREAM team members formed a cross-center focus group with other NLSI teams to further advance the understanding of 1) water migration from poles to mid-latitudes, 2) the manufacturing of OH and water from implantation of the solar wind protons into oxygen –rich regolith and 3) the expectations for LADEE mission (to be launched in 1213) to observe the evidence of water and OH transport. DREAM team members gave key invited talks at the Wet vs Dry Moon workshop and at LPSC 2012 on water migration and manufacturing. We also provided new insights on solar wind ion flow into polar craters; such ions possibly being a sputtering loss process of key volatiles in these regions.

In the latter part of our DREAM studies, we now consider the possibility that all exposed rocky bodies may be prime targets for new reactive chemistry from the space environment. For example, DREAM models were recently adapted to small bodies to infer whether the colder, partially lit regions of Vesta could harbor volatiles. We now consider that even the 'deadest' of rocky bodies may be slowly manufacturing new molecules via reactive chemistry triggered by solar wind implantation. This concept defines our new cross-cutting question: do all exposed rocky bodies manufacture and harbor OH and water? Given an exposed body's continual irradiation by the solar wind and extended exposure to the space environment, that possibility has to be entertained, consistent with the cross-cutting Decadal themes on water, organic synthesis and physical/chemical processes (i.e., Themes #3, #4, and #10).

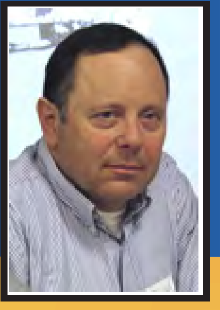
DREAM team members are also active in 'Supporting Other Institute Objectives (SOIO).' DREAM Participated in a number of E/PO events including Maryland Day 2009, 2010, and 2011 at the University of Maryland Campus. DREAM's E/PO team also took a leading role in the formation and implementation of the International Observe the Moon Night. DREAM joined with GSFC's Lunar and Planetary Space Academy on lunar projects for undergraduate science and engineering majors in the summers of 2009-2011. The IT team continued to enhance the DREAM webpage that describes our lunar science (http://ssed.gsfc.nasa.gov/dream/). DREAM E/PO lead Lora Bleacher and Collaborator Noah Petro initiated a new group call the 'Next Generation Lunar Scientist and Engineer (NGLSE)' to engage and develop future lunar scientists and engineers, and to enable their successful involvement in current planning for the scientific exploration of the Moon. DREAM team members are active participants in NLSI's Dust and Atmosphere Focus Group, which advocates for lunar science that especially emphasizes dusty exosphere and plasma research. Team members continue to be recognized as science leaders by chairing conference sessions at LDAP2010, Lunar Science Forum, and LPSC. DREAM press releases and web-features are consistently picked up by the mainstream media and distributed widely, including releases on the electrical lunar polar craters (http://www.nasa.gov/topics/moonmars/features/electric-craters.html), sodium LCROSS ground-based observations (http://www.nasa.gov/mission_pages/LCROSS/news/lunar-water-metal.html), dust-generated electrons (http://science.nasa.gov/science-news/science-at-nasa/2011/14nov_lunarionosphere/), solar storm/lunar atmosphere enhancement (http://www.nasa.gov/topics/solarsystem/features/dream-cme.html) and volatiles at Vesta (http://www.nasa.gov/mission_pages/dawn/news/dawn20120125.html).

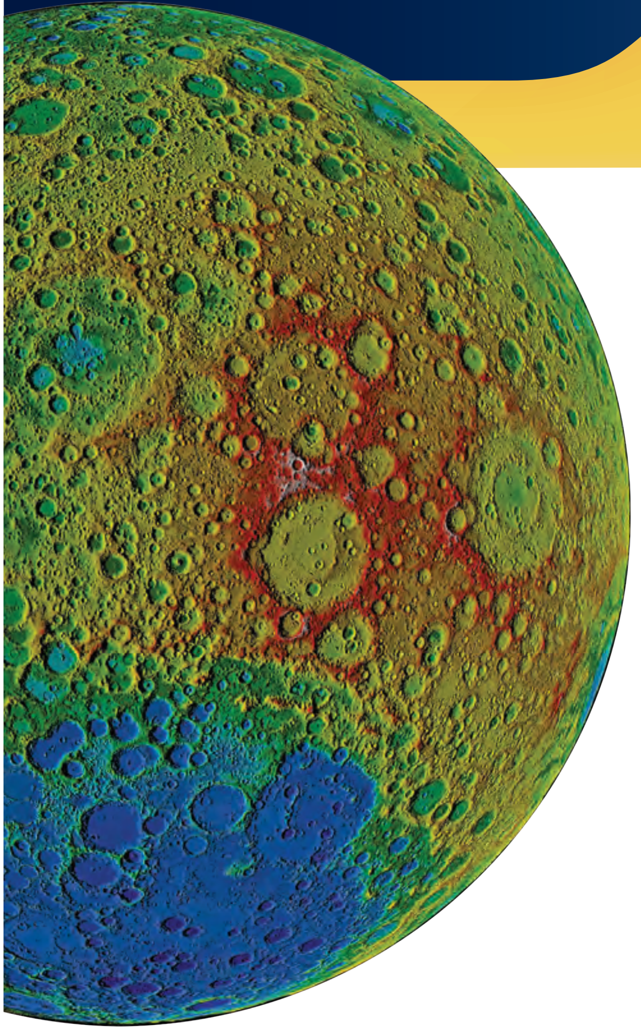
To summarize, the DREAM lunar environment center provides uninterrupted coherency for its researchers, allows immediate reaction & resource deployment to act on new events and finding, and fosters the spirit of community-level cooperation that extends well beyond the boundaries of its own center. All total in the DREAM center's first three program years, the team has submitted 35 science papers to referred journals, provided > 130 talks/presentations at conferences like AGU, Lunar Science Forum, & LPSC, and has mentored over 18 high school and undergraduates via DREAM's Lunar Extreme Program and GSFC's Lunar Planetary Space Academy. The team has initiated > 40 lunar-related investigations that interconnect team members, connect across to other NLSI teams, and link to the international lunar community.

For list of collaborators and other DREAM information, see:

http://ssed.gsfc.nasa.gov/dream/personnel.html and http://ssed.gsfc.nasa.gov/dream/

Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS)





Principal Investigator:
Mihaly Horanyi (U. Colorado)

Tobin Munsat (Deputy PI)	University of Colorado
David Brain	University of Colorado
Mark Cintala	NASA Johnson Space Center
Robert Ergun	University of Colorado
William Farrell	NASA Goddard Space Flight Center
Eberhard Grün	University of Colorado
R. Richard Hodges	University of Colorado
Sasha Kempf	University of Colorado
Giovanni Lapenta	Katholieke Universiteit Leuven, Belgium
Alex Likhanskii	Tech-X, Boulder, Colorado
Gregor Morfill	MPI-E, Garching, Germany
William Peterson	University of Colorado
Stephanie Renfrow	University of Colorado
Scott Robertson	University of Colorado
Ralf Srama	University of Stuttgart, Germany
Alan Stern	Southwest Research Institute, Boulder
Zoltan Sternovsky	University of Colorado
Stein Sture	University of Colorado
Xu Wang	University of Colorado
Michael Weinstein	Zybek, Boulder, Colorado

The Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS) is focused on: a) experimental and theoretical investigations of dusty plasma and impact processes; b) the development of new instrument concepts for future *in situ* dust and plasma measurements on the surface and in orbit about the Moon; and c) a complementary program of education and community development. CCLDAS addresses basic physical and applied lunar science questions, including the long-term usability of mechanical and optical devices on the Moon. CCLDAS is supporting the development of the Lunar Dust Experiment (LDEX), an *in situ* impact dust detector to be flown on the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission scheduled to be launched in 2013.

CCLDAS is a truly interdisciplinary program with researchers, faculty and students from four academic departments at the University of Colorado: Physics, Aerospace Engineering, Civil and Environmental Engineering, and Astrophysical and Planetary Sciences. CCLDAS includes partners at NASA's Johnson Space Center, two small businesses in Boulder, Colorado -- Tech-X and Zybek, and no-cost international partners from Germany and Belgium. Our Co-Investigators represent a wide spectrum in career stages from young assistant professors to leading scientists from the Apollo era.

Our **experimental research program** involves a series of small-scale (< 30 cm) tabletop experiments housed in the Dusty Plasma Laboratory (DPL), and also a large-scale (> 1 m) experimental setup, which includes the development of a 3 MV electrostatic dust accelerator for impact studies, housed in the Lunar Environment and Impact Laboratory (LEIL). LEIL is the cornerstone of our experimental setups, capable of simulating the lunar surface environment, including variable plasma conditions, solar wind, UV radiation, and dust impacts on a dusty regolith surface. The facility is now available for the testing and calibration of plasma and dust instruments, including LDEX for the LADEE mission (**Figure 1**).

Theoretical and modeling studies complement the DPL and LEIL work by addressing the properties of the UV-generated plasma sheath and its interaction with the solar wind plasma flow, and the role of 3D topography in the possible formation of dust ponds, which have been clearly identified in images returned by the NEAR mission on its final approach to the asteroid Eros.

The **development of new instrumentation concepts** includes the laboratory fabrication and test of the Electrostatic Lunar Dust Experiment (ELDA), capable of detecting slow-moving (< 100 m/s) dust particles, and a Dust Telescope (DT), which is a combination of a dust trajectory sensor and a chemical composition analyzer to measure hypervelocity (>> km/s) interplanetary and interstellar dust impacts on the lunar surface.

The University committed two new faculty lines to CCLDAS in order to further strengthen the pool of expertise in lunar sciences and to initiate and teach new lunar science courses. The search for new faculty was successfully completed in 2010, resulting the hiring of David Brain in the Astrophysical and Planetary Sciences Department, and Sascha Kempf in the Department of Physics.

Our research goals remain focused on the processes involved with the atmosphere and dust environment of the Moon accessible for scientific study while the environment remains in a pristine state, one of the high

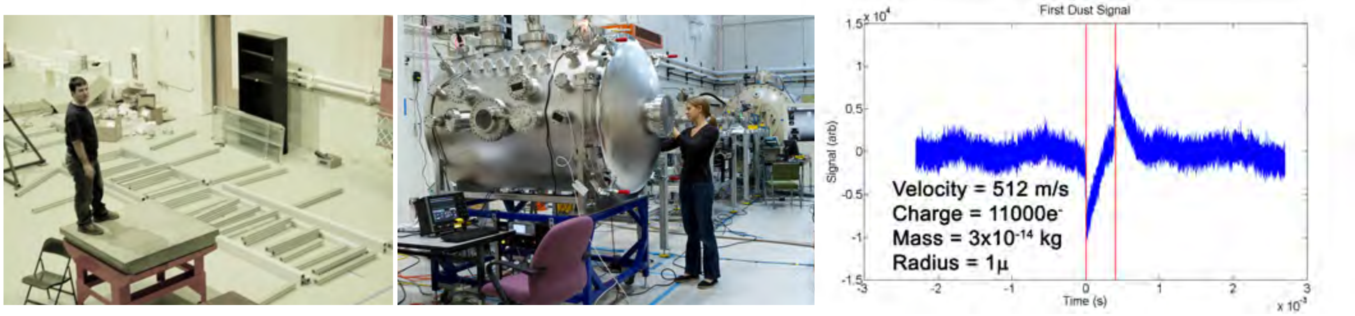


Figure 1. The start of the construction of the CCLDAS dust accelerator at the end of 2009 (left), and the completed facility after recording of our first dust signal in April 2011 (middle). The first recorded dust signal from an in-beam charge pickup-tube detector (right). A time-lapse video of the arrival of the 3MV Pelletron in January 2011, is available online at http://lasp.colorado.edu/ccldas/multimedia.html.

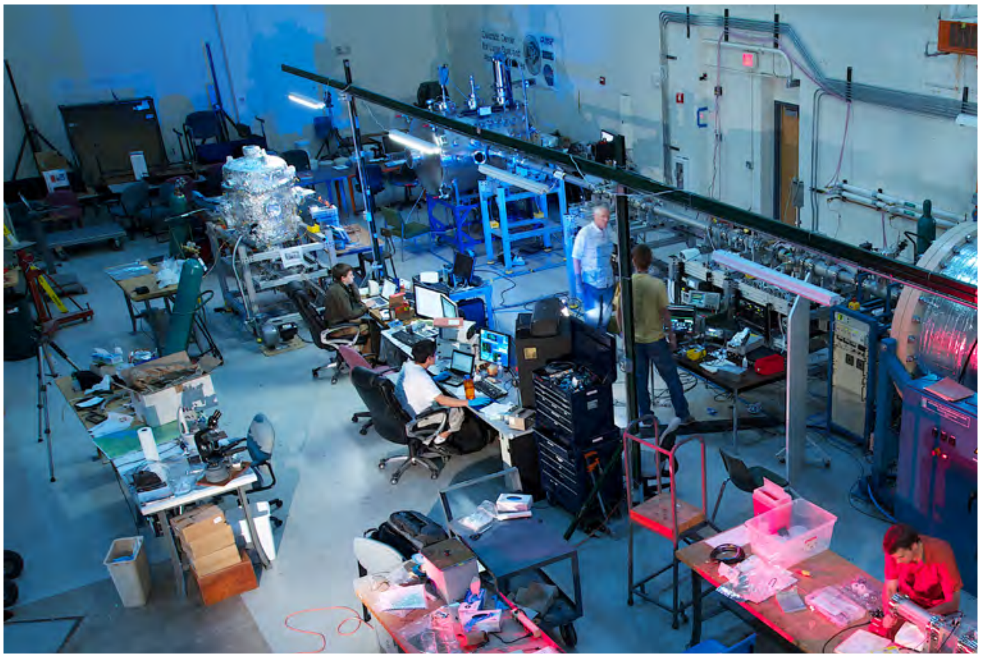


Figure 2. The 3 MV dust accelerator installed at the CCLDAS Lunar Environment and Impact Laboratory. The accelerator is used to simulate the effects of dust impacts with speeds >> 10 km/s for micron sized projectiles. The facility is also used to test and calibrate plasma and dust instruments, including the Lunar Dust EXperiment (LDEX) for the LADEE mission. The facility is now operational and available for the lunar community for impact studies.

priority science concepts (#8) identified by the National Research Council [The Scientific Context for Exploration of the Moon, NRC, 2007 (SCEM)]. CCLDAS research is directed towards the SCEM science goal 8b: Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy.

The 'Heliospheric Science and the Moon' survey [Report to the NASA Advisory Council Heliospheric Subcommittee, 9/2007] identified the need to characterize and understand the interaction of dust and plasma on the surface of the Moon and in the lunar exosphere.

CCLDAS strongly supports future human exploration, as the understanding of the dusty plasma processes can provide a scientific basis for finding effective and economical mitigation strategies for dust hazards. The lunar surface will remain a difficult working environment for humans, and a challenging place to maintain the long-term use of optical and mechanical devices due to dust, UV, and plasma effects.

We are active in the training the of the next generation of multidisciplinary lunar scientists involving graduate, undergraduate and even high school students in our science and engineering projects, involving students from a number of departments across different colleges within the university, including the Physics, Astrophysical and Planetary Sciences, Aerospace, and Civil Engineering.

Lunar Environment and Impact Laboratory (LEIL). A major part of the CCLDAS experimental program is the development of a 3 MV dust accelerator at the new Lunar Environment and Impact Laboratory (LEIL). The objective of the LEIL facility is to accelerate micron-sized grains, which provide a unique research tool to generate high-velocity dust impacts, closely reproducing the effects of micrometeoroid impacts onto the lunar surface. The LEIL facility, including the accelerator itself and the accompanying target chambers, has been developed to simulate the lunar surface environment, including variable plasma conditions, solar wind, UV radiation, and dust impacts (**Figure 2 and 3**).

Experimental Impact Studies. During the first few months of operation, the accelerator has been used for a number of initial experiments. In one run, for example, a sample of 7 μm thick aluminized mylar foil was placed into the beam line to assess the possibility of using thin foils as a secondary ejecta detector for micrometeorite impacts (**Figure 4**). This experiment is part of an ongoing series to characterize the relationship between thin films, impactor characteristics, and the resulting cratering and/or penetration details. This study has immediate applicability to polyvinylidene fluoride (PVDF) as a dust detector, and it may lead to fundamental improvements to our understanding of PVDF detector signals.

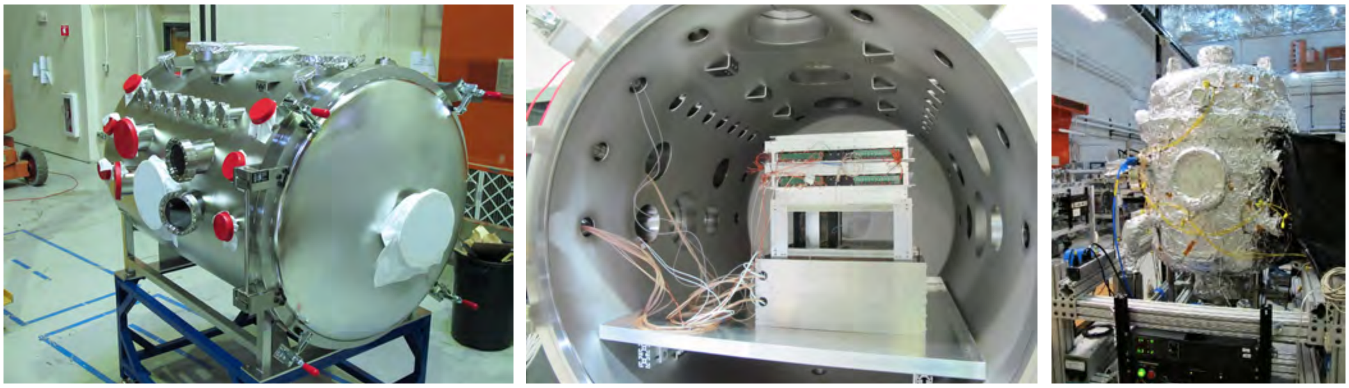


Figure 3. The Lunar Environment and Impact Laboratory PRIMARY chamber exterior (left) and interior (middle) housing a dust-trajectory instrument for testing. This impact chamber will house UV, electron, and ion sources to simulate the variable plasma conditions on the lunar surface, and acts as a target chamber for the dust accelerator. The UHV (right) chamber is designed for experiments of impact products, where ultra-high vacuum conditions are required.

Silicon Nitride windows from the Solar Probe Plus mission were studied in the accelerator to assess the damage from hypervelocity impacts. These windows are extremely thin, and there is a concern that hypervelocity dust penetrations can lead to damage that propagates along the surface. In the initial tests, this did not occur, and follow-up tests will be carried out in the future.

In another experiment, several samples of fused silica were placed into the beam line in order to characterize the damage from micrometeorites on lunar retro-reflectors. The resultant craters were imaged using a scanning electron microscope (SEM), showing craters approximately 0.7-3 μm in diameter. Future work includes determining the depth of the craters and whether the flakes are chemically similar to the coating of the sample. This is also part of an ongoing study to evaluate materials and their applicability as barriers to micro-particles. Samples of carbon, stainless steel, tungsten, and molybdenum have also been exposed the dust beam for this purpose.

Inter-Team Collaborations:

DREAM and CCLDAS. Andrew Poppe and Mihaly Horanyi (CCLDAS) worked with Jasper Halekas, Greg Delory, and Bill Farrell (DREAM) on the analysis and interpretation of observations made by Lunar Prospector (LP) of the lunar surface potential in both the terrestrial plasma sheet and the solar wind. The Electron Reflectometer on LP reported large negative surface potential over the lit side of the Moon, contradicting all theoretical expectations. Recently developed theoretical and simulation models suggest the formation of non-monotonic potential structures above the dayside lunar surface with a large negative potential minimum above the surface, while still maintaining a positive charge density of the surface, offering a long-awaited theory to explain the LP findings.

LUNAR and CCLDAS. Doug Curry (LUNAR) is leading an effort to develop a new generation of corner-cube retro-reflectors for laser ranging. He has brought sample reflectors to the CCLDAS dust accelerator to investigate the effects of hypervelocity dust impacts on the optical properties of the sample. This early experiment will be followed up with a systematic study of crater forming impacts on optical devices.

Brown U. and CCLDAS. Initial experiments to investigate space weathering due to dust impact are scheduled in the spring of 2012. Basalt samples will be exposed to hyper-velocity (> 1 km/s) iron dust impacts to identify changes in their reflectance spectra. If successful, a follow up series experiments is planned to use different dust compositions, and to establish a scaling between the number of dust impacts per unit surface area and the geologic exposure time.

International Partners. CCLDAS closely collaborates with the dust group at the Max-Planck-Institute for Nuclear Physics, Heidelberg (MPI-K), and the University of Stuttgart, Germany, both members of the German Lunar Science Institute. CCLDAS greatly benefited from these collaborations in the development

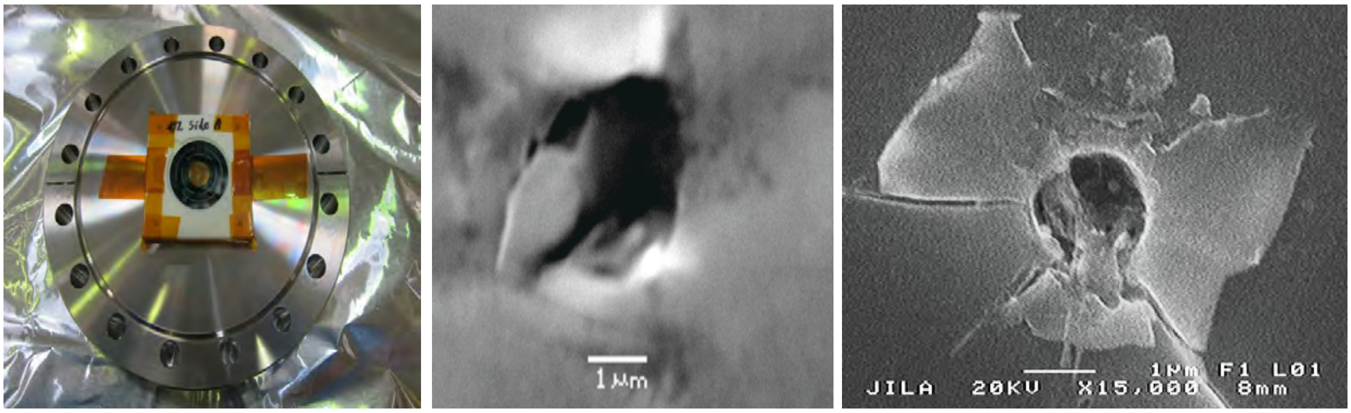
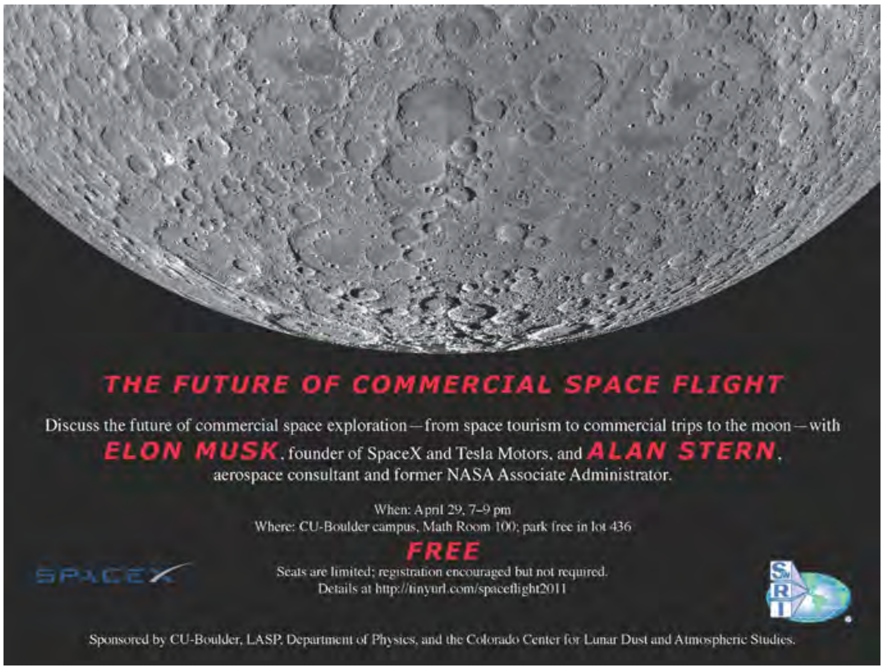


Figure 4. Images of various experiments from the initial accelerator runs. At left is a foil sample from Solar Probe Plus. The center photograph shows the penetration damage at high magnification. Micrometeoroid damage to a fused quartz retroreflector sample is shown at right.

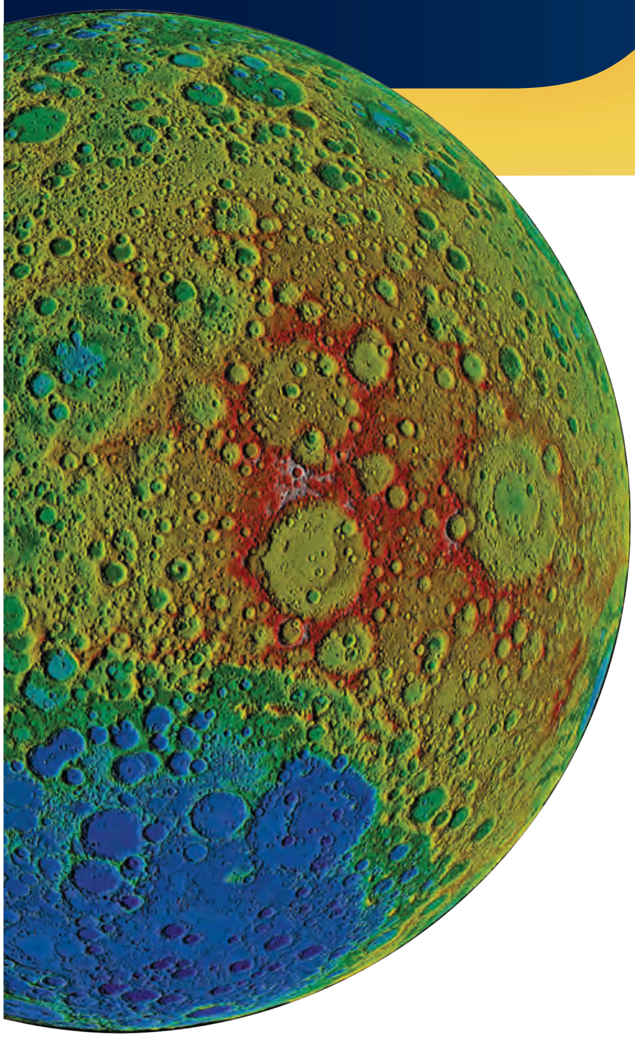
of our dust accelerator facility. We have an active exchange program for postdocs and researchers, and initiated establishing a student exchange program that will also include formal class work, in addition to involvement in our experimental programs. Anna Mocker (U. of Stuttgart) is a visiting scholar at CCLDAS for the period of 8/2011 - 12/2012. CCLDAS graduate student Anthony Shu (supported by NLSI) spent three weeks at the MPI-K dust accelerator.

E/PO Highlights. Eleven nationally recognized journalists and six scientists, as well as astronaut Jeff Ashby, attended our May 2010 workshop for media professionals. Our April 2011 public symposium 'The Future of Commercial Space Flight' featured nationally known entrepreneur Elon Musk, as well as former NASA Associate Administrator and CCLDAS member Alan Stern (www.youtube.com/watch?v=ZQcZ9pKsliQ). CCLDAS has initiated the LunGradCon series in conjunction with the NLSI Lunar Science Forum conferences to enhance the professional development of graduate students and early postdoctoral researchers.

Online Presence:
Webpages: http://lasp.colorado.edu/ccldas/
Student Blog: http://ccldas.blogspot.com/
Flickr: www.flickr.com/photos/ccldas/
Webcam: http://dustcam.colorado.edu



Center for Lunar Science and Exploration



Principal Investigator:
David A. Kring (LPI/JSC)

Eileen Stansbery (Deputy PI)	NASA Johnson Space Center
Jaclyn Allen	NASA Johnson Space Center
Donald Bogard	NASA Johnson Space Center
Alan Brandon	University of Houston
David Draper	NASA Johnson Space Center
Everett Gibson	NASA Johnson Space Center
Jose Hurtado	University of Texas – El Paso
John Jones	NASA Johnson Space Center
Walter Keifer	Lunar and Planetary Institute
Lindsay Keller	NASA Johnson Space Center
Thomas Lapen	University of Houston
Cin-Ty Lee	Rice University
Gary Lofgren	NASA Johnson Space Center
Patrick McGovern	Lunar and Planetary Institute
David McKay	NASA Johnson Space Center
Wendell Mendell	NASA Johnson Space Center
Charles Meyer	NASA Johnson Space Center
David Mittlefehldt	NASA Johnson Space Center
Clive Neal	University of Notre Dame
Marc Norman	Australian National University
Laurence Nyquist	NASA Johnson Space Center
Kevin Righter	NASA Johnson Space Center
Stephanie Shipp	Lunar and Planetary Institute
Jonathan Snow	University of Houston
Paul Spudis	Lunar and Planetary Institute
Timothy Swindle	University of Arizona
Allan Treiman	Lunar and Planetary Institute
Richard Walker	University of Maryland
Michael Zolensky	NASA Johnson Space Center

The NASA Lunar and Planetary Institute (LPI) and the Johnson Space Center (JSC) have a long and successful history of collaborative research and exploration activities that began with the Apollo program. The LPI and JSC have harnessed that heritage to develop the Center for Lunar Science and Exploration (http://www.lpi.usra.edu/nlsi/) to better support our nation's science and exploration activities. The Center is designed to (1) develop a core, multi-institutional lunar science program that addresses the highest science priorities identified by the National Research Council (NRC) for NASA; (2) provide scientific and technical expertise to NASA that will infuse its lunar research programs, including developing investigations that influence current and future space missions; (3) support the development of a lunar science community that both captures the surviving Apollo experience and trains the next generation of lunar science researchers; and (4) use that core lunar science to develop education and public outreach programs that will energize and capture the imagination of K-14 audiences and the general public. To meet those objectives, we developed programs for scientific research, exploration, training, and education and public outreach. Each of those programs and a summary of activities are presented here.

Science. The NLSI program fosters collaborative, multi-institutional work that takes advantage of long-distance networking technologies. We have organized a team involving faculty, students, and analytical facilities at Rice University, the University of Arizona, University of Houston, University of Maryland, and University of Notre Dame. We have also established international partnerships with faculty, students, and analytical facilities in Australia, India, Japan, and the United Kingdom.

At the core of the Center's activities is a series of studies (Fig. 1) to test the giant impact hypothesis for the Moon's origin; the lunar magma ocean hypothesis and its implications for differentiation of all terrestrial planets; and the lunar cataclysm hypothesis, which has become a critical measure of events involved in the

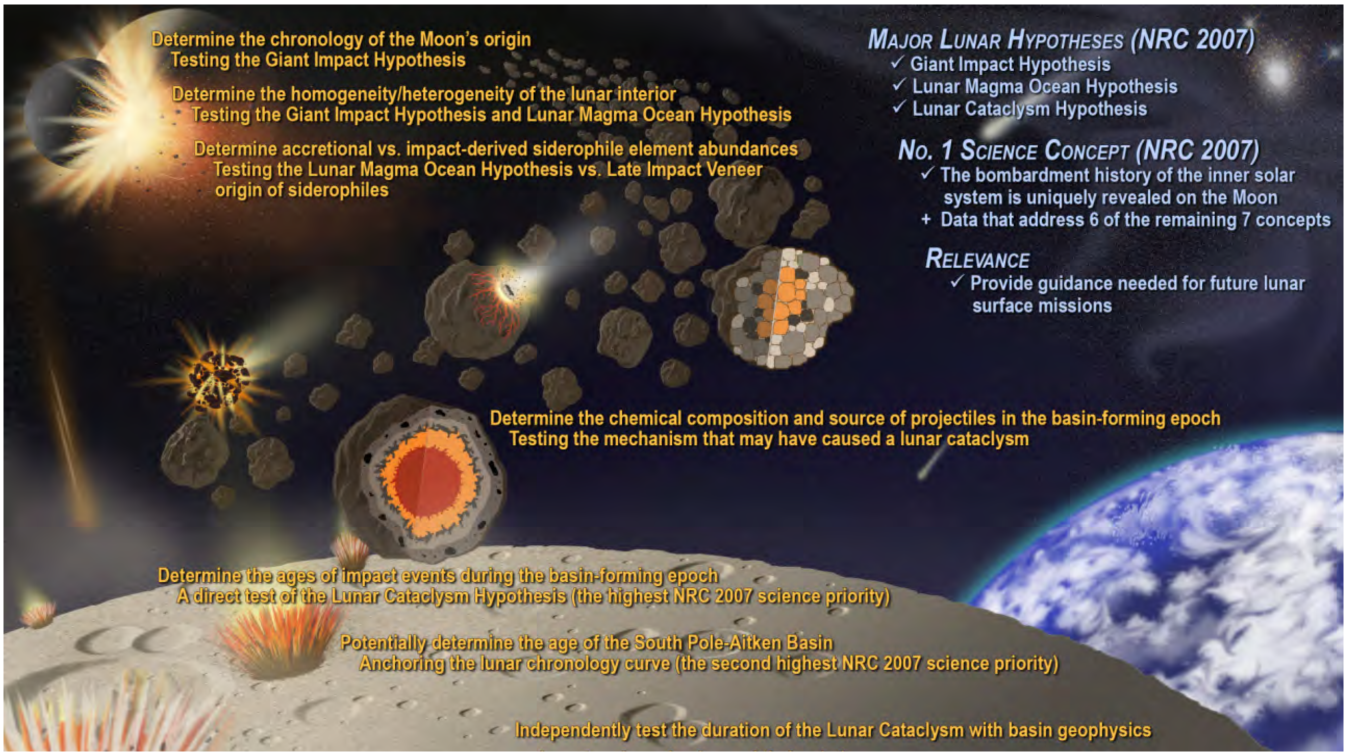


Figure 1. The Center for Lunar Science and Exploration team is investigating impact cratering, which is the dominant geologic process affecting the lunar surface and intimately involved in the Moon's origin. The theme that runs through our science initiative is tied directly to the major lunar hypotheses, science concepts, and highest science priorities identified by the NRC (2007). Our projects trace the origin and evolution of the Moon from the hypothesized giant impact origin (upper left corner), through the collisional evolution of debris in the solar system (mid-panel) that produced the great basin-forming epoch on the Moon and potentially a lunar cataclysm (lower left), to the continued impact production and gardening of the lunar regolith (lower right). Scientific bonuses of this work include an evaluation of the Moon's primordial crust, diversity of crustal lithologies, and distribution of basin-epoch lithologies at future landing sites, which are additional targets of the NRC (2007) report.

accretion and orbital evolution of planetary bodies in both the inner and outer solar system. That period of bombardment may also be intimately linked with the origin and early evolution of life on Earth (Fig. 2). The scope of our work encompasses seven of the eight science concepts identified by the National Research Council (2007) for NASA's Science Mission Directorate (SMD), although our focus is on the highest-priority science concept (the bombardment history of the inner solar system as uniquely revealed on the Moon) and highest-priority goal (to test the lunar cataclysm hypothesis). It also addresses at least two priority questions of Planetary Sciences in the Decade 2013-2022 and provides baseline studies for the recommended New Frontiers South Pole-Aitken sample return mission. To illustrate our integrated approach, we outline a subset of our results regarding our investigation of the earliest collisions to have affected the Moon.

We begin with the discovery of a spectacular meteoritic relic from a planetesimal collision that occurred before the Moon had even formed [Weirich et al. 2011]. After the Moon accreted, collisions repeatedly modified its crust and upper mantle. Hydrocode modeling of the formation of the oldest and largest basin on the Moon, the South Pole-Aitken Basin, indicates a significant amount of mantle material was melted and incorporated into a central melt zone [Potter et al., submitted], thus providing a key compositional parameter for the identification of impact melts associated with that event and its age. Modeling of other basins is underway [Potter et al. 2011], which is providing the input needed to evaluate post-impact evolution of the lunar crust [Kiefer et al. 2011]. We found that basins may have influenced stresses in the lithosphere and the eventual eruption of basalts on the lunar surface [McGovern and Litherland 2011]. In parallel, we used LRO data to show that the outer rings of the Orientale Basin, the youngest and best preserved basin, formed along 30 km deep normal faults [Nahm and Kring 2011] in a manner similar to that seen at the Chicxulub impact crater on Earth.

During the basin-forming epoch, the Moon's crust and upper mantle were repeatedly affected by impacting asteroids. Using a new tool to probe the most ancient lunar terrains, we discovered a shift in the size distribution of craters that implies asteroid impact velocities doubled at the beginning of the lunar cataclysm, sometime between the formation of the South Pole-Aitken and Nectaris basins [Marchi et al. 2012], consistent with a shift in the orbits of Jupiter and other outer solar system planets. A new photogeologic assessment of the Apollo 17 landing site suggests more basins were produced between the Serenitatis and Imbrium impact events than previously thought [Spudis et al. 2011], implying a far more dramatic lunar cataclysm.

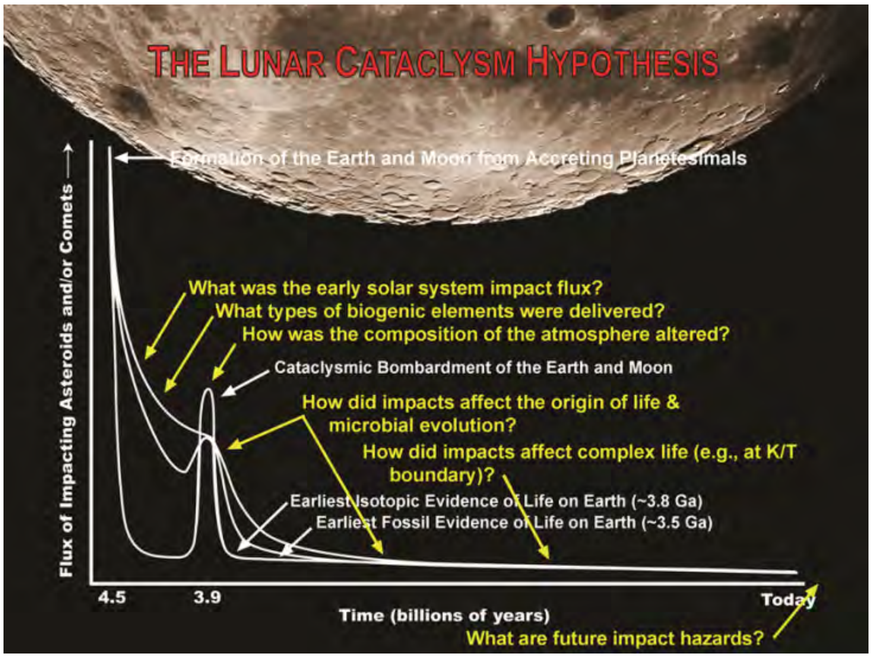


Figure 2. A schematic diagram illustrating the lunar cataclysm hypothesis, uncertainties associated with it, and the fundamentally important questions associated with that impact flux. Apollo sample analyses suggest there was a spike in the impact rate about 3.9 Ga and that the last of the basin-forming impact events on the Moon occurred ~3.8 Ga. The magnitude and duration of that spike is unclear, as is the impact flux between 4.5 and 4.0 Ga. (After Kring, 2003).

We are continuing to probe the source of debris hitting the Moon during the basin-forming epoch and compare it to more recent times using newly developed techniques to measure highly siderophile elements and Os-isotopes. Analyses of Apollo impact melt samples [Galenas et al., 2011] indicate some were produced from known meteoritic sources, while others were produced by projectiles that are not represented in the current meteoritic inventory. Not only are we painting

Figure 3. Team members have participated in four lunar and one near-Earth asteroid mission simulation at the Black Point Lava Flow planetary analogue site. Tests involved detailed crew traverses and a trade study between unpressurized crew rover and pressurized crew rover (seen here). Geologic tools were located on the aft deck of the rover. Crew egressed through suit ports on a platform near the geologic tool storage rack. Photo credits: NASA JSC (left) and David A. Kring (right).

a definitive view of projectile sources, it is fueling a new assessment of the biogenic elements added to Earth.

Because impact melts are the key to determining the cadence of impact activity, we have developed easy-to-use analytical expressions for calculating impact melt volumes for impacts of any trajectory into the Moon and any other terrestrial planetary surface [Abramov et al., in press]. We are also mapping the location of impact melt deposits on the lunar surface that are suitable for future sample return missions [Öhman and Kring, 2012], while developing and implementing a training program for astronauts that may be tasked to collect those samples (Kring 2011; Kring and Hörz 2011; Kring and Lofgren 2011).

Exploration. We are using our team's extensive experience with lunar surface samples, impact cratered terrains, and volcanic terrains to integrate science and exploration activities. We led the scientific support for several lengthy simulations of missions to the Moon and near-Earth asteroids at the Black Point planetary analogue terrain in northern Arizona (Fig. 3). In 2010, for example, our team helped develop a detailed 28-day-long mission plan for the Malapert Massif region within the South Pole-Aitken Basin, which was then simulated at the Black Point site. This year we led the science plan for near-Earth asteroid mission operations. These simulations involve the Lunar Electric Rover/Space Exploration Vehicle and the astronaut office.

As the community develops the architecture and hardware to return to the lunar surface, our team has developed a series of studies to determine where on the lunar surface the NRC's highest science objectives can be achieved. We have determined that one of the best sites for testing the lunar cataclysm hypothesis is Schrödinger Basin [O'Sullivan et al. 2011; Kramer et al., in prep.]. At that locality, we should be able to determine the age of the oldest basin (South Pole-Aitken) and that of the second youngest (Schrödinger), thus bracketing nearly the entire basin-forming epoch.

Interestingly, Schrödinger also contains volcanic deposits of Eratosthenian and Copernican age, thus providing two additional benchmarks in the evolutionary stratigraphy of the Moon. We are currently developing mission concepts to Schrödinger using stand-alone robotic assets and robotic assets that are assisted by crew from an Orion platform at the Earth-Moon L2 position.

Figure 4. One of the highlights of our training activities is the Field Training and Research Program at Meteor Crater. In 2010 we hosted 19 Ph.D. and 5 M.S. students and in 2011 12 Ph.D. and 4 M.S. students. Here, four students are studying impact ejecta with CLSE PI Kring.

Training. Future space exploration depends critically on our ability to train young people. The Center is developing a pipeline of talent that feeds into research and development programs associated with both SMD and HEOMD. The Center's programs have engaged 11 post-doctoral fellows and ~100 graduate students thus far.

A highlight of graduate student training is our Lunar Exploration Summer Intern Program, which has hosted seven teams in an intensive and immersive study of lunar landing sites where the NRC (2007) science objectives can be addressed. Those results have been so successful that they have been repeatedly briefed to ESMD and HEOMD staff, including the Lunar Destinations portion of NASA's Human Spaceflight Architecture Team (HAT).

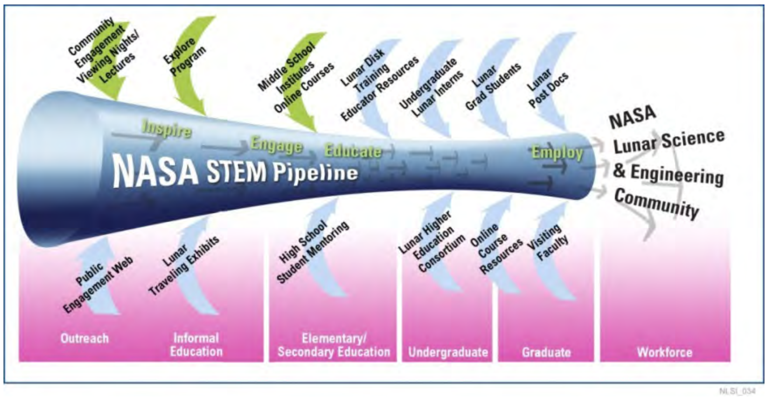


Figure 5. Outreach, informal education, and high school mentoring feed students into the undergraduate and graduate student training activities and, eventually, the professional science and exploration communities.

Another highlight of graduate student training is the Field Training and Research Program at Meteor Crater (Fig. 4), the world's best preserved impact crater. Skills developed during the training program have better prepared the students for their own thesis studies in impact cratered terrains on the Earth, Moon, Mars, and other solar system bodies. The research component has also led to significant discoveries at Meteor Crater (Kring et al. 2011, 2012).

A third major component of our training activities is the *Lunar Consortium for Higher Education*, which involves a large number of university faculty who are developing on-line material that teachers anywhere in the world can access and incorporate into their classrooms.

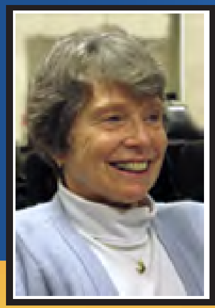
Education and Public Outreach. The results of our science investigations are being mined to generate a dynamic education and public outreach (E/PO) program. Activities are designed to assist teachers with their classroom activities, and reach students at all levels. The Center for Lunar Science and Exploration is building on a long heritage of E/PO products generated by the LPI and JSC staff that feed forward to the university programs that we support (Fig. 5). We have, for example, sponsored lunar research projects at 19 high schools nationwide that involve 27 teams and 169 students, including those in under-represented and under-served populations. We have also created a series of library exhibits that have been distributed to 24 unique locations that have reached 100,000 people in special library programs thus far.

Cross-cutting Products. Our team has generated cross-cutting products that serve the science, exploration, education, and public communities. One of our product highlights is the *Lunar Science and Exploration Portal* (http://www.lpi.usra.edu/lunar/), which is designed to be an on-line gateway to lunar information. Over 5 million page views have been recorded thus far (>5000/day). That product includes a *Lunar Sample Atlas* (42,000 images), *Apollo Image Collection* (32,000 images), a *Virtual Microscope*, and an immense collection of lunar science and exploration documents.

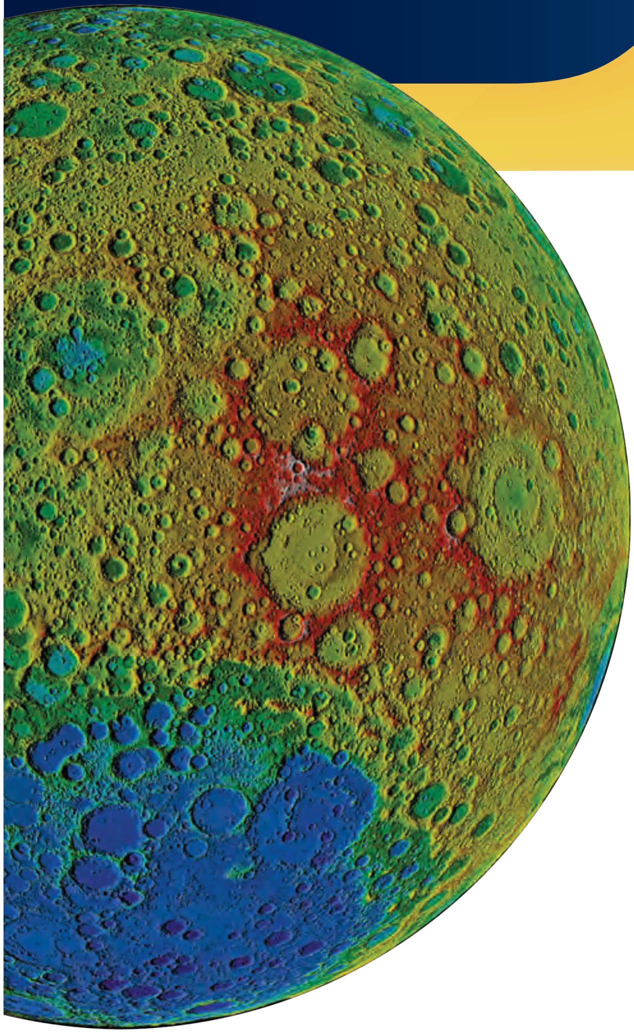
Conclusions. We note that this integrated set of activities could not have been accomplished without the administrative and funding structure provided through the NASA Lunar Science Institute program. That architecture is very efficient and maximizes the productivity of the team and, thus, greatly enhances our ability to provide NASA the products it needs.

Finally, the response from students has been amazing. Lunar missions are inspiring our youth and encouraging them to participate in science and technological fields, fulfilling another important objective for the nation.

The Moon as Cornerstone to the Terrestrial Planets



Principal Investigator:
Carle Pieters (Brown/MIT)



Maria Zuber (Deputy PI)	Massachusetts Institute of Technology
Alexander Basilevsky	Vernadsky Institute
Reid Cooper	Brown University
Melinda Dyar	Mount Holyoke College
Linda Elkins-Tanton	Massachusetts Institute of Technology
Ian Garrick-Bethell	Massachusetts Institute of Technology
Timothy Grove	Massachusetts Institute of Technology
Erik Hauri	Carnegie Institution of Washington
James Head	Brown University
Paul Hess	Brown University
Harald Hiesinger	Westfalische Wilhelms Universitat Munster
Yan Liang	Brown University
Bernard Marty	CRPG-CNRS
Igor Mitrofanov	Institute for Space Research
John Mustard	Brown University
Stephen Parman	Brown University
Sally Ride	Imaginary Lines Inc.
Cassandra Runyon	College of Charleston
Malcolm Rutherford	Brown University
Alberto Saal	Brown University
Peter Schultz	Brown University
Yuriy Shkuratov	Kharkov National University
Suzanne Smrekar	Jet Propulsion Laboratory
Lawrence Taylor	University of Tennessee
James Van Orman	Case Western Reserve University
Benjamin Weiss	Massachusetts Institute of Technology
Lionel Wilson	Lancaster University
Jack Wisdom	Massachusetts Institute of Technology
Michael Wyatt	Brown University

Our Brown/MIT NLSI team is jointly hosted by Brown University and the Massachusetts Institute of Technology by faculty who share a long history of science interactions. Our combined team began with 19 Co-investigators and 13 named Collaborators from 8 institutions, including 6 active foreign collaborators. The flexible structure of NLSI has allowed some scientists to move in and out of this group over the last three years, while the team as a whole has remained active and focused.

Productivity enabled by NLSI continues to grow. The principal objective of our NLSI Team has been to establish a center of excellence for lunar science that will not only produce the next generation of knowledgeable and qualified lunar scientists, attract some of the best minds into the field and keep them involved, but also lay the groundwork for future exploration. Our integrated implementation plan is specifically designed to accomplish this while creating the environment for active interaction of some of the top scientists involved in lunar research along with their students. The components central to our NLSI team are illustrated in Figure 1 and include four specific science themes that build on our strengths, four implementation pillars that form our integrated implementation plan, and a strong infrastructure of laboratories and facilities that supports these lunar science activities.

Our NLSI Science Themes echo the first three (priority) science concepts of the 2007 NRC recommendations on the "Scientific Context for Exploration of the Moon." These deal with the early history and evolution of the Moon as a planetary body: its bombardment history, the structure and character of the interior, and the character and compositional diversity of the crust. The more recent directions of our Brown/MIT group fall solidly within the top two science goals of the more recent 2011 NRC Decadal report "Visions and Voyages" for the study of the inner planets. Specifically, we address a wide range of the origin and diversity issues of planetary evolution, and our work on lunar water is at the core of understanding water in the solar system, the necessary ingredient for life.

We are committed to Looking toward the Future and integrating our activities with NASA's long-range programs. We have established a science pipeline with former astronauts (Dave Scott of Apollo 15 who regularly visits Brown for science discussions) as well as current Astronauts (Dos Equis) in training for future missions.

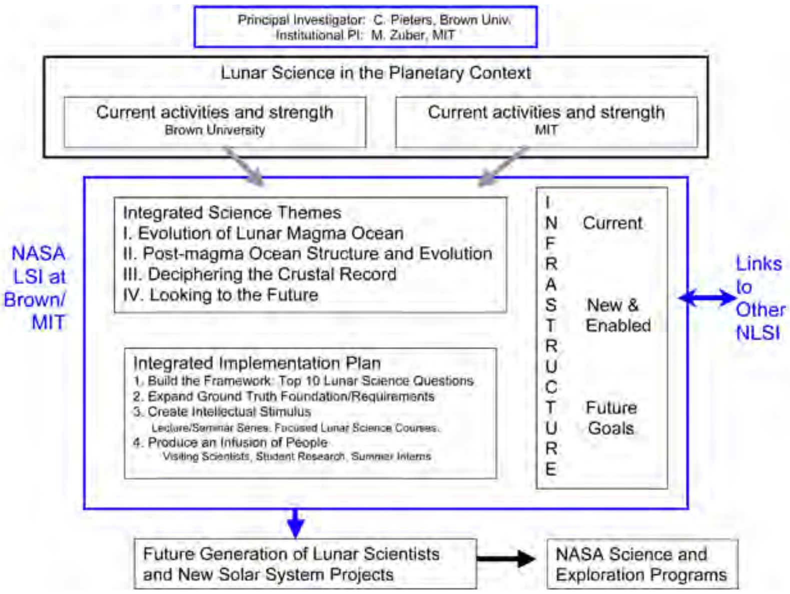
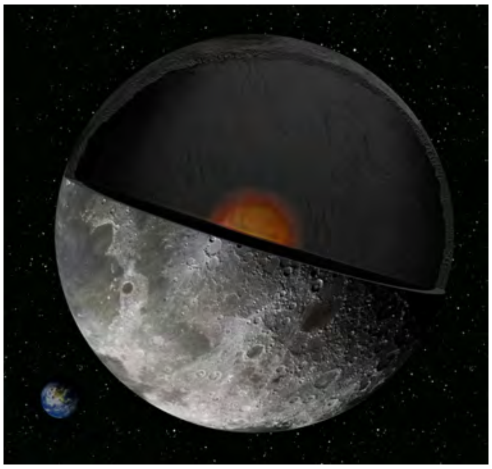


Figure 1. Science Themes and Integrated Implementation Plan of the Brown/MIT NASA Lunar Science Institute.

Figure 2. Top: At a meeting at Brown University, Apollo 15 Commander David R. Scott (left) discusses plans for human and robotic lunar exploration with six MIT students from Earth and Planetary Sciences and Aero/Astro. Bottom: At Brown University, Brown Professors Jim Head (left) and Sergei Khrushchev (middle), Apollo 15 Commander David Scott (second from right), and Apollo 15 Flight DIrector Gerry Griffin (right), discuss past and future exploration plans with members of the 20th NASA astronaut Class (Dos Equis), from left, Jeanette Epps, Reid WIseman, Serena Aunon, Kjell Lindgren, and Jack Fischer.



A Long-Lived Lunar Core Dynamo

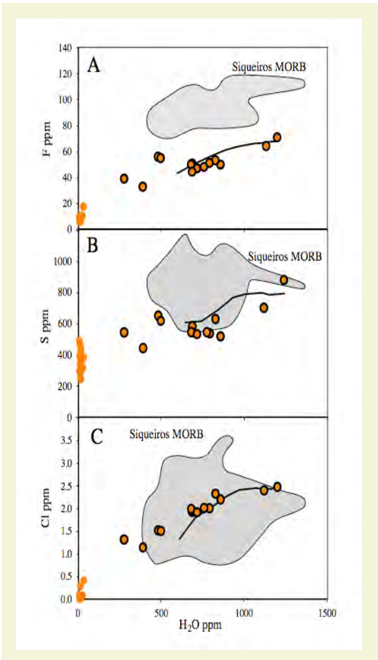
Erin K. Shea,1 Benjamin P. Weiss,[1] William S. Cassata,[2] David L. Shuster,[2,3] Sonia M. Tikoo,[1] Jerome Gattacceca,[4] Timothy L. Grove,1 Michael D. Fuller[5]*

Paleomagnetic measurements indicate that a core dynamo probably existed on the Moon 4.2 billion years ago. However, the subsequent history of the lunar core dynamo is unknown. Here we report paleomagnetic, petrologic, and 40Ar/39Ar thermochronometry measurements on the 3.7-billion-year-old mare basalt sample 10020. This sample contains a high-coercivity magnetization acquired in a stable field of at least ~12 microteslas. These data extend the known lifetime of the lunar dynamo by 500 million years. Such a long-lived lunar dynamo probably required a power source other than thermochemical convection from secular cooling of the lunar interior. The inferred strong intensity of the lunar paleofield presents a challenge to current dynamo theory.

Recent examples from our Science Themes and Implementation Plan are highlighted here, but discussed in more detail in the documents and publications resulting from this work (see attached bibliography) as well as the body of the report.

Accurately constraining early interior processes of the Moon is an important but difficult challenge. Some of our recent successes have come from extracting the paleomagnetic record from carefully chosen well-characterized lunar samples using modern equipment. A highly significant result was recently published in *Science* with MIT graduate student Erin Shea as first author [January 2012]. The NLSI team has provided solid evidence not only that the Moon had a significant core and dynamo, but that the dynamo was active at least until 3.7 billion years ago (when many mare basalts were emplaced).

The origin, character, and distribution of lunar water have not only sparked great public interest and curiosity, but analyses of these properties have enormous scientific value. Our NLSI team has been involved with all forms of water discovered on the Moon. First, in 2008 Saal et al. reported the first measurement of lunar water and new volatile contents (H_2O, F, S, Cl) in single lunar glass beads and concentration profiles across beads of very-low-Ti glasses. In volatile-volatile plots the concentration profiles in a single bead implied a degassing process. Degassing models suggested an initial water concentration of ~ 750 ppm, with a minimum of 260 ppm at the 95% confidence level. Probing further, in 2011 the same group reported volatile contents in lunar melt inclusion (inclusions within crystals within glass of the primitive melt) confirming our early predictions that the volatile contents of lunar volcanic glasses were equivalent to those found in MORB [Hauri et al. 2011]. This new study includes scientists from two



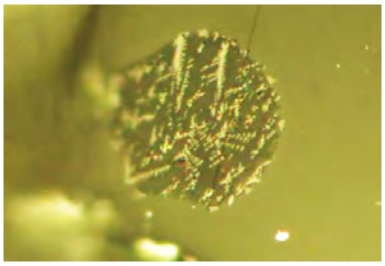


Figure 3. Volatile content of melt inclusions [Hauri et al., 2011].

High Pre-Eruptive Water Contents Preserved in Lunar Melt Inclusions

Erik H. Hauri,[1] Thomas Weinreich,[2] Alberto E. Saal,[2] Malcolm C. Rutherford,[2] James A. Van Orman[3]*

The Moon has long been thought to be depleted in volatiles such as water, and indeed published direct measurements of water in lunar volcanic glasses have never exceeded 50 parts per million (ppm). Here, we report in situ measurements of water in lunar melt inclusions; these samples of primitive lunar magma, by virtue of being trapped within olivine crystals before volcanic eruption, did not experience posteruptive degassing. The lunar melt inclusions contain 615 to 1410 ppm water and high correlated amounts of fluorine (50 to 78 ppm), sulfur (612 to 877 ppm), and chlorine (1.5 to 3.0 ppm). These volatile contents are very similar to primitive terrestrial mid-ocean ridge basalts and indicate that some parts of the lunar interior contain as much water as Earth's upper mantle.

NLSI centers as well as students.

Secondly, the discovery of widespread lunar surficial OH/H_2O, whose origin appears to be linked to solar wind processes [Pieters et al., Science, 2009], sparked new directions in lunar sample investigations as well as new detailed compositional analyses of lunar terrains with remote data. Some of the new analyses are led by our NLSI team members, but the interest spans the community as a whole. Using the now public M^3 data from the Chandrayan spacecraft, we have identified a few local areas on the lunar surface that are extremely water-rich. The most prominent are found on the farside, and manuscripts discussing the implications of this discovery for lunar crustal evolution are in preparation. A generic association of OH with composition has been found that is likely due to mineral physics processes. Specifically, mafic-rich basaltic areas do not attract much OH/H_2O, whereas anorthositic areas are highly correlated with surficial OH/H_2O. This relation is illustrated in Figure 4 [see student report: Cheek et al. 2012].

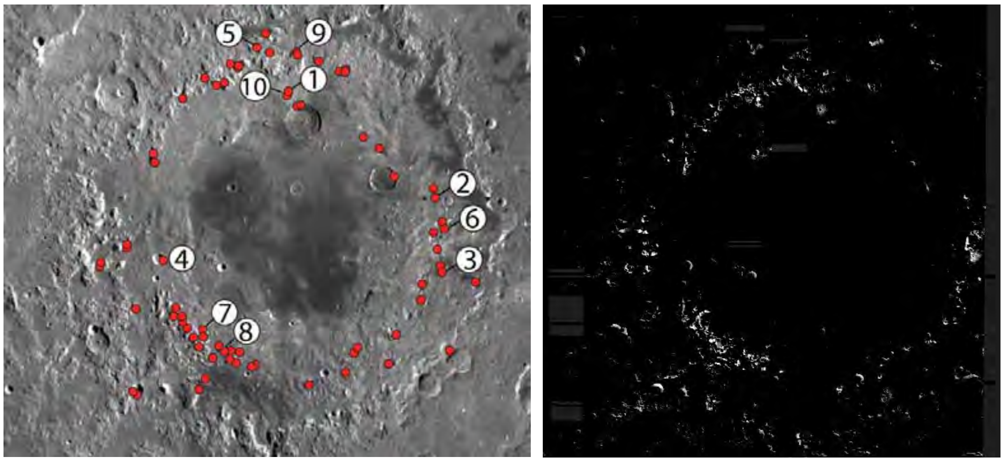


Figure 4. *[Left] Outcrops of crystalline anorthosite identified in the Orientale region with M3 data based on a highly diagnostic 1.25μm absorption feature [Cheek et al., 2012]. The pure anorthosite is massive and concentrated along the Inner Rook Mountains. [Right] Band depth for OH feature at 2.8μm across the Orientale region derived from M3 data. The presence of OH is highly correlated with massive anorthosite.*

The discovery of a *new* lunar rock type that is dominated by Mg-spinel has created intense interest and discussion. Its geologic setting implies it is associated with deep-seated crustal material, and several independent experimental programs have been initiated across the community to characterize this new rock type and constrain crustal evolution.

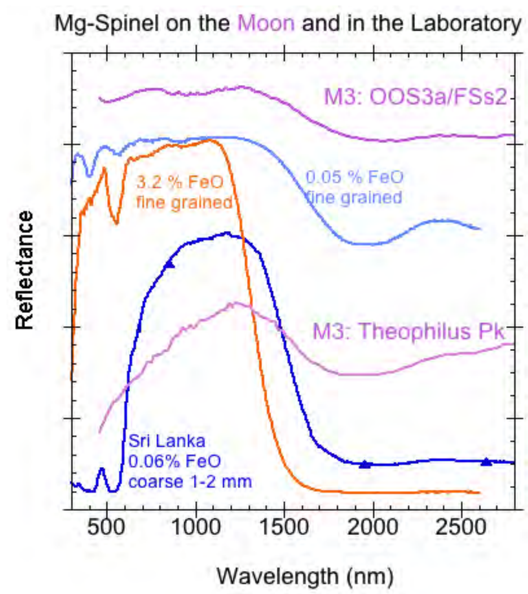
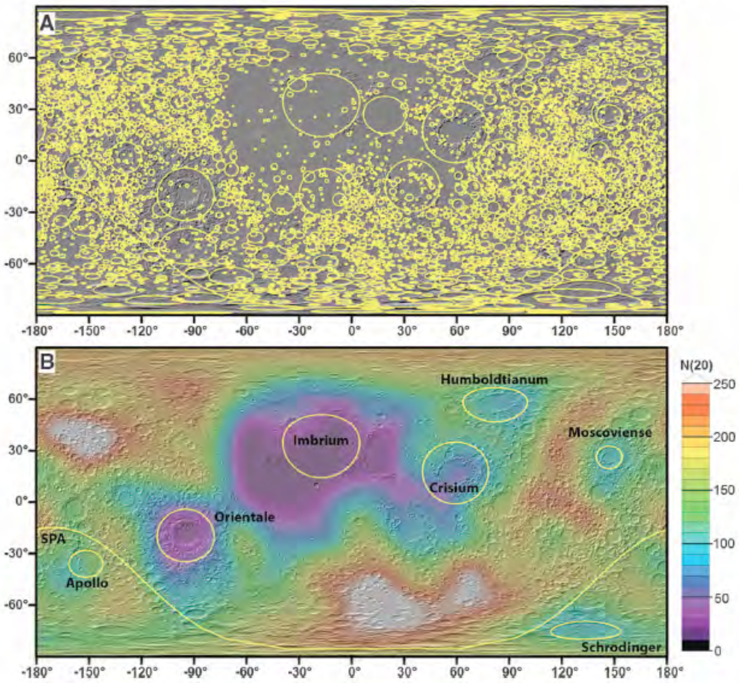


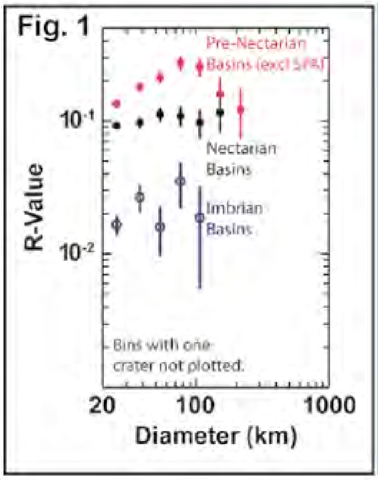
Figure 5. Spectra of Mg-spinel measured on the Moon by M3 (shown in purple) and example laboratory experiments designed to constrain the amount of FeO present [see student report by Jackson et al., 2012].

The Moon has retained the record of the bombardment history for our part of the solar system at 1 AU. The high accuracy of LRO LOLA data has allowed properties of craters to be measured unambiguously across the Moon. Derived crater size-frequency distributions (CSFDs) shown in Figure 6 for Pre-Nectarian, Nectarian, and Imbrian basins allow the bombardment history of different epochs to be evaluated and compared [Head et al., 2010].

Nectarian basins have a distribution consistent with the late Population 2 impactors (mare-like). The Pre-Nectarian basins, however, are more similar to the early Population 1 impactors. This suggests a transition from predominantly Population 1 to Population 2 impactors must have occurred by the mid-Nectarian in this part of the solar system [Fassett et al., 2012].

The Brown/MIT NLSI **TEAM** is committed to the philosophy that '**T**ogether **E**veryone **A**chieves **M**ore'* and works closely together to execute a dynamic Education and Public Outreach (E/PO) program in support of the NLSI, as coordinated by the NLSI Central Office. The E/PO team is committed to supporting a unified lunar E/PO program for NASA and the NLSI. Four E/PO goals have guided our efforts and directly support NASA's E/PO outcomes (e.g., NASA DRAFT Ed Mgmt Plan, p. 9, Jan. 2006); Table D1): 1) Rekindle humankind's sense of wonder with the Moon, 2) Inspire and motivate the next generation of lunar explorers, 3) Broaden student knowledge of the early Earth-Moon history, 4) Increase underrepresented / minority participation in exploring the Moon. The breadth of our program and examples of each component are documented in our full E/PO report.





Global Distribution of Large Lunar Craters: Implications for Resurfacing and Impactor Populations

James W. Head III,[1] Caleb I. Fassett,[1] Seth J. Kadish,[1] David E. Smith,[2,3] Maria T. Zuber,[2,3] Gregory A Neumann,[3] Erwan Mazarico[2,3]*

By using high-resolution altimetric measurements of the Moon, we produced a catalog of all impact craters ≥20 kilometers in diameter on the lunar surface and analyzed their distribution and population characteristics. The most-densely cratered portion of the highlands reached a state of saturation equilibrium. Large impact events, such as Orientale Basin, locally modified the prebasin crater population to ~2 basin radii from the basin center. Basins such as Imbrium, Orientale, And Nectaris, which are important stratigraphic markers in lunar history, are temporally distinguishable on the basis of crater statistics. The characteristics of pre- and postmare crater populations support the hypothesis that there were two populations of impactors in early solar system history and that the transition occurred near the time of the Orientale Basin event.

BIBLIOGRAPHY

NASA LUNAR SCIENCE INSTITUTE

BIBLIOGRAPHY

This bibliography represents the peer reviewed papers in journals, conference proceedings and books produced during the Institute's first three years. In addition to the 235 scientific publications listed here, NLSI teams have presented ~1,100 extended abstracts, conference papers, oral and poster presentations.

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