

**NASA LUNAR SCIENCE INSTITUTE**  
***FOURTH YEAR REPORT***

2012-2013

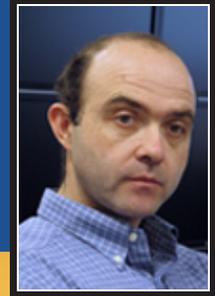


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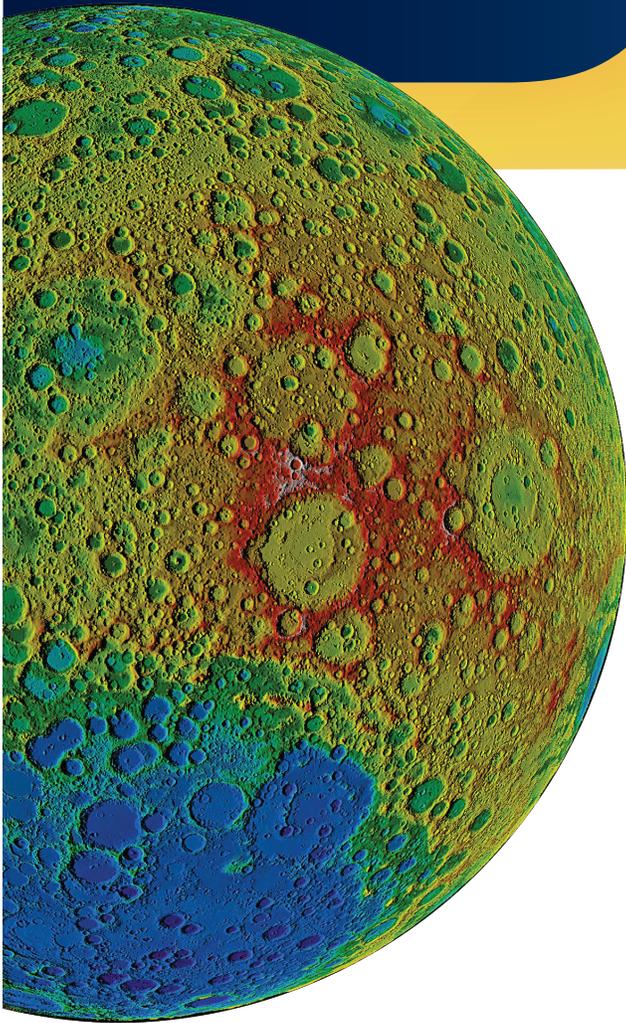
# ***INTRODUCTION***

The NASA Lunar Science Institute (NLSI) is proud to present this summary of the accomplishments in the fourth year of operations. This report contains executive summaries highlighting the accomplishments of NLSI's seven U.S. teams from 2012-2013. A complete bibliography of peer-reviewed scientific publications can be found at <http://lunarscience.nasa.gov/science-library/>

# Science and Exploration of the Lunar Poles



*Principal Investigator:  
Ben Bussey (JHU/APL)*



**4<sup>th</sup> Year Report for the “Polar” Team**  
**PI: Ben Bussey (JHU/APL)**

**Introduction:** During the 4<sup>th</sup> year of this research effort we have continued to turn the lunar polar regions from “*Luna incognita*”, the unknown Moon, in to “*Luna cognita*”. The continued goal of our team has been 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.

**1. Team Research Reports**

*Polar Geology:* In the final year of the current award period, we have continued studies that have been shown to make the most progress towards understanding the geological nature and occurrence of polar ice deposits on the Moon.

The analytical model for detecting patchy or buried ice deposits from Lunar Reconnaissance Orbiter (LRO) Mini-RF image data has been used to identify several craters near both poles that probably contain ice. These maps of model ice locations are being used to identify targets for bistatic data collection to be undertaken by the Mini-RF team using the Arecibo radio telescope in the coming year. We have identified two principal classes of crater: those containing ice patches and those having thick deposits covered by a thin layer of dry regolith (Thompson et al., 2012). Initial results show that most potential ice locations are concentrated in small craters within 5° of the poles. Some of these model results have been incorporated into a new paper summarizing Mini-RF results for the anomalous craters near the poles.

We have previously reported the results of an affordable lunar return architecture based on the teleoperation of robotic assets in Earth-Moon space. In the past year, we have advised and worked with a team of graduate students to identify possible landing sites near the south pole and plan exploratory traverses to examine and characterize polar volatile sites. Several possible sites and corresponding sample traverses near the south polar crater Amundsen have been mapped and described. Continued work will focus on future potential robotic traverses to map ice-harvesting sites that could be incorporated into a resources-based cis-lunar architecture.

*Polar Illumination Studies:* We have located portions of the lunar surface that have been persistently shadowed over geologic time periods as far from the pole as  $\pm 58^\circ$  of latitude. These results were obtained by application of a ray tracing technique (developed during the earlier portion of this NLSI study) to the latest instrument datasets from the LRO. To the best of our knowledge this is the first complete mapping of permanent shadows that are detectable at the resolution provided by current datasets. Our analysis reveals that 13,361 km<sup>2</sup> of surface in the northern hemisphere and 17,698 km<sup>2</sup> in the southern hemisphere that are permanently shadowed. We have produced maps showing the locations of all permanent shadows detectable using these data.

We then conducted detailed analyses on the permanent shadows farthest from the poles. Surface brightness temperature data derived from the LRO Diviner mid-infrared radiometer were analyzed for four of these non-polar locations and found to have mid-day temperatures 75 to 120 K less than nearby comparison sites that experience direct daytime illumination. In some cases, the permanently shadowed areas have nighttime temperatures 10 to 25 K lower than surroundings; supporting our conclusions. The surface brightness temperature results also raise interesting questions about their ability to cold trap volatiles. Discovery of these non-polar permanently shadowed regions plausibly increases the yield of water resources and high priority exploration targets on the Moon.

*Excavation & Mobility Modeling:* The excavation and mobility modeling project primary focus is to develop the Controllable objects - unbound particles interaction (COUPi)

discrete element method (DEM) model of excavation and wheel interaction with regolith. This involves conducting excavation, wheel digging, and penetration experiments to guide and validate development of the DEM; the development is also guided by CRREL-DEM expert consultation. CRREL-DEM simulations are also used to develop approaches to simulating wheels and excavation in regolith for transfer into COUPi.

The experimental phase of the work is complete with test data for penetration, wheel digging, and excavation (quasi-static and percussive) being used in various DEM simulation efforts. This past year has been spent preparing papers related to the experimental results.

As part of their excavation testing, GRC developed a preliminary method of obtaining dynamic full-field surface profiles on simulant soil beds, which can be used to better understand soil deformation and failure fields during excavation and mobility testing and to guide and validate DEM simulations (Figure 1). The results of this work have been published.

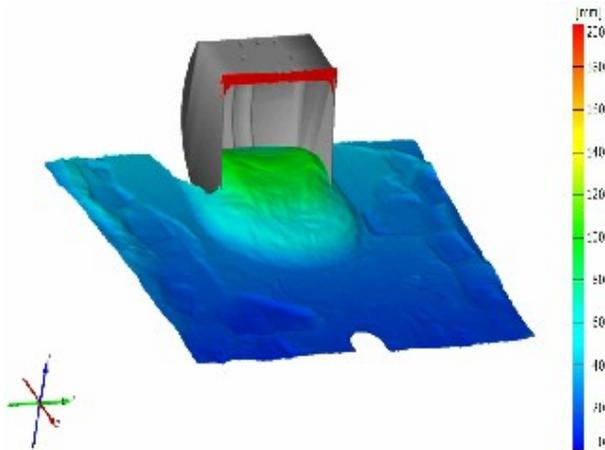


Figure 1. An instantaneous surface profile plot of an excavator bucket in GRC-3 lunar simulant soil

Simulation of wheel digging using the CRREL DEM is complete with results published. The CRREL DEM simulation for excavation [percussive and quasi-static] are also complete with some results presented at Earth and Space 2012 and a journal article in progress.

The COUPi DEM is fully functional and can run on laptop or fully parallel computer systems. The recently released version has benchmarked a speedup of 3.5 times on four processors compared to single

processor calculations, with future speed increases expected in the near future through architecture efficiency improvements and ability to run on larger arrays of processors.

COUPi is being beta tested at GRC by Allen Wilkinson to simulate cone penetration tests (CPT). Cone penetration tests were done at several different regolith densities and COUPi is being used to develop different density DEM particle beds with log-normal particle size distribution to simulate the test results. Controlling how DEM particle beds settle to obtain different DEM packing densities is not generally done because of its difficulty. However, since packing density is a strong factor in determining regolith strength, we have developed several ways to control density. We are currently building our CPT simulation particle beds and plan to run simulations within the next few weeks. We are concurrently preparing a paper on the CPT simulations and hope to have it completed by the end of April. This, however, depends on the rate of simulation progress and we will continue working on the simulation into a no-cost extension period to its completion.

In support of COUPi, a visual particle creation tool that allows the user to create designer particles from basic shapes is near completion. This is significant as it will allow creation of DEM particle shapes that more closely represent natural particle shapes (e.g., matching CT imaged particles with DEM particles).

*Polar Volatile Modeling:* A new version of the impact gardening model has been developed that is now fully 3-dimensional (Figure 2). It implements a simple approach to estimate the frequency with which ice sheets remain intact under the influence of impacts. The model follows the topography changes of an area over time as impacts occur. If one assumes that initially there was

an ice layer at a certain depth with a certain thickness, then any impact that penetrates to the ice layer would remove ice from that location. Conversely, if no impacts penetrate to the ice layer, then no ice is lost from that location. Therefore, the model tracks both the current and minimum surface altitudes.

Initial applications of the model have been promising. The results appear consistent with the conclusions derived by the more-limited two-point model (Hurley et al., 2012). For example, the conclusion that a 10 m roving distance provides a very high likelihood that a rover in a PSR would be able to reach an enriched area is still consistent with the new model. Future work will study the expected heterogeneity of ice in lunar permanently shadowed regions.

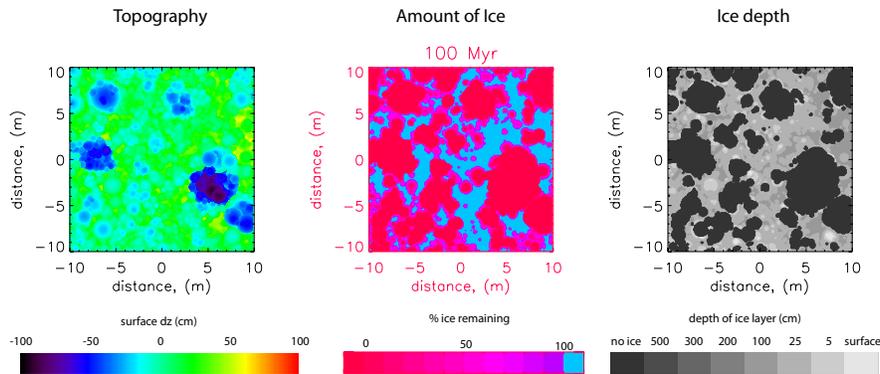


Figure 2. Example simulation of impact gardening on a 20 m x 20 m area on the Moon after 100 Myr. The resulting topography is on the left. Then, assuming there was a 10 cm thick ice layer from the surface to 10 cm depth at  $t=0$ , the model estimates the amount of ice remaining in each location (center) (see text for model assumptions). On the right, the figure shows the depth to ice remains.

*Earth Observation:* We have pursued the concept for compact, robust full Stokes spectropolarimetry that was invented during the previous year. We have enhanced our laboratory optical bench, and begun installing a similar system at NIST, in Gaithersburg MD, to facilitate improved calibration and a broader testing scope. With this concept, spectropolarimetry from space becomes a very viable proposition. The concept was published in Sparks et al. (2012a, b), and is also under consideration for an ESA equivalent instrument, LOUPE (Karalidi et al., 2012).

We continued to compare LCROSS observations of Earth to the NAI Virtual Planetary Laboratory VPL state-of-the-art Earth model which simulates the spatially- and temporally-dependent appearance of Earth to a distant observer. We have simulated all three LCROSS Earth observation epochs, and are developing new tools to interpret the results. (The LCROSS field of view was smaller than the entire disk of Earth, so that only portions of Earth's disk were sampled.) We highlighted the strength of the UV ozone absorption edge in the empirical Earth spectrum, and pointed out that in the case of the Earth, this arises from the presence of life. The feature has the potential to provide a biosignature, albeit with the risk of false positives, presented at UV Astronomy, HST and Beyond (2012).

We have pursued the use of circular spectropolarimetry as a possible biosignature, due to the chiral interaction of microorganisms with light, from a theoretical standpoint (Kolokolova et al 2012), and presented a discussion of the utility of a survey of the surface of Mars (Sparks et al. 2012b).

*Ground Penetrating Radar:* Ground Penetrating Radar (GPR) data from terrestrial analogs sites can help define the lunar near-surface properties at the meter to sub-meter scale required for designing and implementing *in situ* geologic and engineering experiments. Moreover, GPR data may help place constraints on the source of reflections or characteristics observed in orbital LRO

SAR data. Existing GPR systems are being configured with a suite of antennas to collect data up to about 10 m depth and at resolution of several 10's of cm. We also anticipate using a low power, 400-600 MHz GPR system called *STRATA* that was designed for future deployment on the belly of a rover or buggy.

Work to over the past year has focused on two major tasks: conducting field work with the GPR in analog environments (e.g., Washington State and Hawaii); and collaboration with the Moon and Mars Analog Mission Activities team at JSC to outfit a rover with our GPR during field trials in Hawaii. A paper related to earlier results of GPR interrogation of ejecta deposits at Meteor Crater, AZ is in revision.

*Neutron Spectrometer Analysis:* Progress for the neutron topic area during year four covers a number of different items. First, several papers were published describing the statistical analysis studies of orbital neutron data measured from the Lunar Prospector (LP) and LRO spacecraft (Miller et al., 2012a, b, c). These studies present the development of a new analysis technique for determining the statistical robustness of mapped orbital neutron data. This technique was applied to a combined dataset from the LP and LRO spacecraft that resulted in the first combined analyses of these data. One new finding is a statistically significant fast neutron signal at the Moon's South pole. A future publication that explores the significance of this fast neutron detection is in preparation (Miller et al., 2013, in preparation).

A second primary area of progress was the successful publication of a new technique for deriving lunar compositional variations using high energy gamma-ray (HEGR). Specifically, HEGR have energies between 8 and 9 MeV. Their compositional variability was fortuitously observed when researching LP neutron and gamma-ray data for lunar hydrogen studies. As described by Peplowski and Lawrence (2013), HEGR provide a good measure of lunar magnesium concentrations. While not explicitly related to lunar hydrogen concentrations, deriving a new measure of magnesium provides key information about surface compositional variability, from which variations in hydrogen concentrations can be derived and understood.

Finally, a study was completed where particle transport models and measured energetic particle data were used to estimate the possible production of organic material at the lunar poles. The results of this work were presented at the Fall AGU 2012 meeting and as well as submitted for peer review publications (Crites et al., 2013).

*Volatile Laboratory Studies:* This year we focused on documenting results from previous experiments and further developing models for: 1) the loss of OH from the very near surface mainly by hydrogen migration, and 2) the migration of water in the lunar surface, and 3) accounting for the spectral nature of the OH on the lunar surface. We have published one peer-reviewed article detailing our Temperature Programmed Desorption experiments that were conducted in years 2 and 3 using particulate samples and the subsequent derivation of the activation energy for the water.

## **2. Inter-team Collaborations**

The collaboration between the polar volatiles group, the volatiles laboratory group and a subset of the GSFC DREAM team has continued. Teleconferences have helped guide the modelers on the DREAM team to use the most recent laboratory numbers in their models. They have also helped guide the laboratory group to perform experiments on much needed physical values under relevant conditions.

Dr. Sparks's is collaborating with Kimberly Ennico (LCROSS) on analysis of LCROSS Earth observations. This collaboration arose solely because of activities in the NLSI and was initiated prior to the LCROSS observations. LCROSS observed the Earth three times from the UV to mid-IR and represent one of the best datasets for space observing of the Earth. Hence they form a

significant fraction of the work being carried out within our study.

Polarimetry team in the Netherlands, originally Utrecht now Leiden:

- Developed precision polarimetry concept for observing biological scenery “TreePol” based on modulating FLCs. Student project administered by F. Snik.
- Developed polarimetric concept for obtaining precision polarimetry with static optics, suitable for space application (Sparks et al., 2012 including F. Snik). Included in ESA instrument concept Lunar Observatory for Unresolved Polarimetry of Earth (LOUPE, Karalidi et al., 2012).

Theoretical work on scattering from chiral substances with L. Kolokolova (College Park, MD), her graduate student L. Nagimunov, and Prof. D. Makowski (Auburn University).

Peter McCullough has fostered a collaboration with John Kielkopf, University of Louisville, to make Earthshine polarizations observations with a 0.5-m student telescope at Kentucky. A summer student Gabriella Hodosán has been working with McCullough on these data.

We have a long standing collaboration with Thomas Germer, Optical Technology Division, National Institute of Standards and Technology on the use of precision polarimetry as a biosignature, which is a critical element of our project, and Prof. Frank Robb at the UMD School of Medicine, a microbiologist expert in extremophiles.

Formal collaboration with the Moon and Mars Analog Mission Activities (MMAMA) team from JSC in 2012 resulted in contribution of our GPR to their analog rover payload. Post-doc Patrick Russell participated in the integration of the GPR into the payload and in field trials in Hawaii during 2012.

A collaboration has been developed with NASA Langley Research Center to simulate asteroid capture and control dynamics scenarios. A simulation of asteroid creation from separated particles under low self-gravitational attraction was developed along with a simple asteroid capture simulation using a powered net.

A collaboration has also been developed with the JPL Mars Exploration Rover mission, Ray Arvidson, and the MIT mobility laboratory to simulate high slip rover wheel mechanics to develop parametric data on wheel slip, sinkage and torque to feed into the ARTEMIS rover dynamic models of the MER. ARTEMIS also is used to simulate MSL rover traverses. The MER rover wheel CAD has been imported into COUPi and MER wheel high slip/sinkage data from MIT have been obtained in preparation for MER wheel simulations. The MER wheel CAN has been imported into COUPi with simulations planned to start in April.

**3. EPO Report** – In 2012, the Education and Public Outreach effort for APL’s NLSI team continued to engage a variety of audiences with lunar science and ongoing research of the Institute. This included activities targeting formal education (K-12 and Higher Education) and Informal Education audiences. The year started off with a lecture, as part of the Higher Education Seminar Series, in partnership with the Maryland Space Grant Consortium. NLSI APL scientist Dr. Rachel Klima visited Capitol College in Maryland and presented her work in a presentation titled, “*The Colorful Moon: Exploring Mineralogy and Water/OH- on the Lunar Surface.*” This lecture was recorded and is archived, along with other lectures from this Seminar Series, on the LunarPoles.jhuapl.edu website. Another higher education activity was the participation of a Geology undergraduate student in the NLSI research through the NASA/APL Summer Internship Program. Her project included laboratory work that advances our

understanding of how to identify and study pyroxene-rich rocks from orbit, such as those types of rocks on the lunar surface.

Formal education activities for the K-12 audience included a student event and professional development for science teachers. The student event, Space Academy, was held in spring of 2012 and included over 100 students from local middle schools. This Space Academy focused on NLSI research as well as the Mini-RF instrument engineering and science. Space Academy is intended to inspire and excite students on the many types of space-related careers that exist, using staff from APL (including NLSI researchers) to breakdown stereotypes of scientists and engineers. Professional development for middle and high school educators was offered through the fourth annual Unknown Moon Institute Educators workshop, a 4.5 day workshop that highlights the main research topics of NLSI through hands-on activities and scientist lectures. This workshop is planned and implemented in partnership with the Lunar and Planetary Institute, and the 2012 workshop was also held at LPI, and included tours to Johnson Space Center. About 25 educators attended and the evaluation for the workshop included many high marks for content, lectures, hands-on activities and usefulness in the classroom.

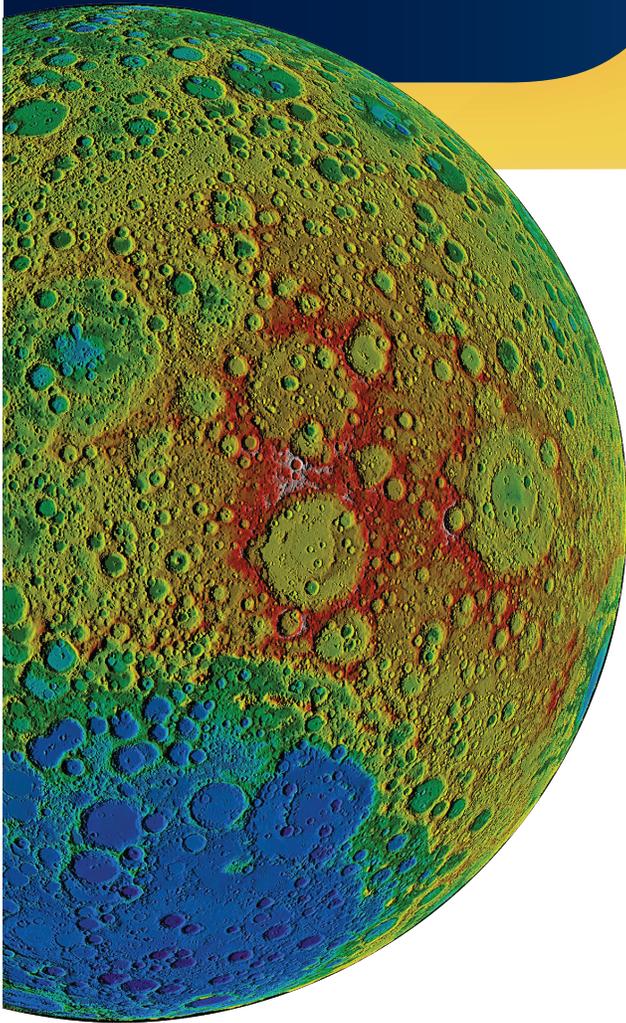
The APL team partnered with the Maryland Science Center (MSC) to celebrate International Observe the Moon Night as part of its informal education activities. This is the third year that the APL team has celebrated InOMN with MSC and public access to MSC's rooftop observatory, equipped with a computer controlled Alvan Clark and Sons 8" refracting telescope. Three APL scientists were available at this event to answer questions and help the public enjoy their night observing our Moon. Additionally, APL had a booth at the 2012 AGU Fall Meeting Exploration Station public event, where lunar science and NLSI research was shared with the public through hands-on activities and a Magic Planet display showing Mini-RF global data of the Moon. Magic Planet is a spherical display that is very popular with young crowds, and especially useful in displaying global data and generating discussions on comparative planetology.

Lastly, the APL NLSI website ([lunarpoles.jhuapl.edu](http://lunarpoles.jhuapl.edu)) was recently updated with a list of publications for the APL team's first three years of research and results.

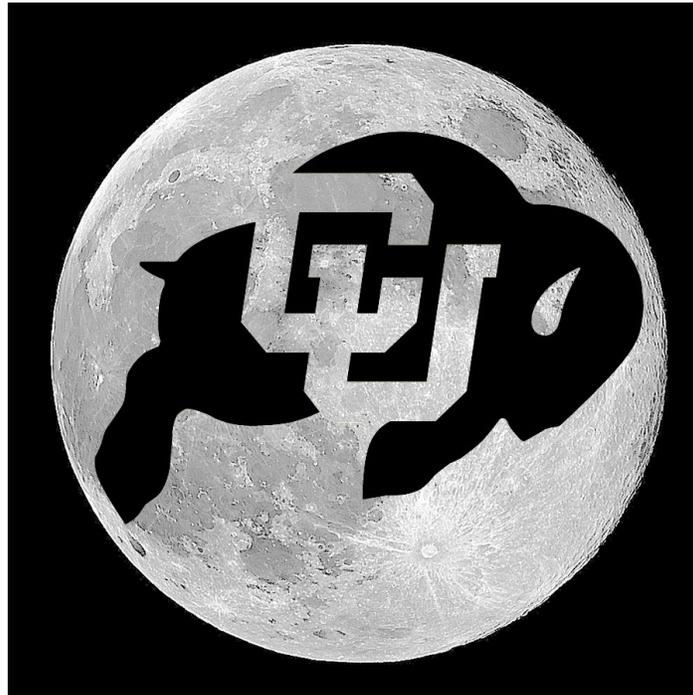
# Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS)



*Principal Investigator:  
Mihaly Horanyi (U. Colorado)*



**NASA Lunar Science Institute:  
Colorado Center for Lunar Dust and Atmospheric Studies**



**Report for Year 4**

**4/15/2012 - 12/31/2012**

## 1. Summary

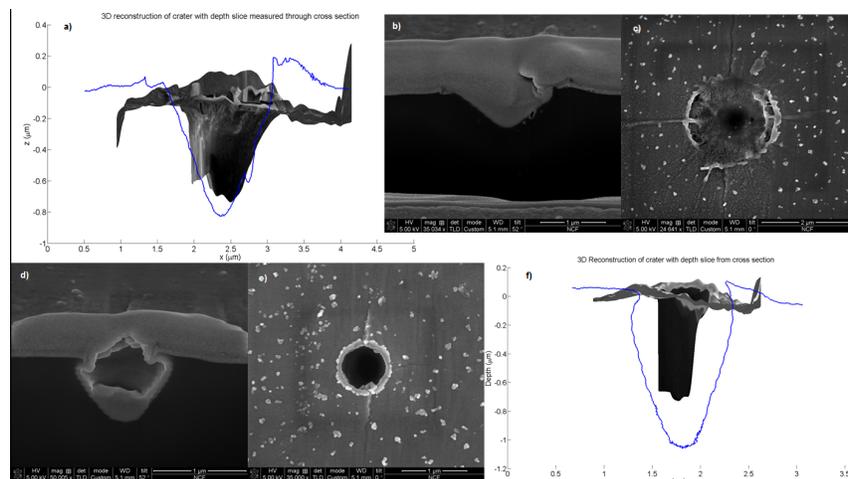
In its fourth year of funding, the Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS) remained focused on: **a)** experimental and theoretical investigations of dusty plasma and impact processes; **b)** the development of new instrument concepts for future in situ dust and plasma measurements on the surface and in orbit about the Moon; and **c)** a complementary program of education and community development. CCLDAS addressed basic physical and applied lunar science questions, including the long-term survival of mechanical and optical devices on the Moon. CCLDAS enabled 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.

## 2. Project Reports

### Accelerator Projects

The summary of the current status and technical capabilities of the CCLDAS dust accelerator were published (A. Shu, *et al.*, *Rev. Sci. Instruments* **83**, 075108, 2012). Major improvements include the completion, software development, and full integration of a new dust beam profiler (P. Northway, *et al.*, *Measurement Science and Technology* **23**, 105902, 2012), as well as the successful characterization of an FPGA-based digitally filtered particle selection unit (E. Thomas, *et al.*, *Planetary and Space Sci.*, submitted, 2012). The accelerator was utilized by several external groups in preparation for submitting their proposals to various NASA programs.

Our first complete set of thin-film damage studies has been submitted for publication to the special issue of Planetary and Space Science organized by CCLDAS (A. Shu *et al.*, Cratering Studies in Polyvinylidene Fluoride (PVDF) Thin Films, *Planetary and Space Sci.*, submitted, 2012). Several ongoing experiments have been designed, and their initial results reported, on the production of ions, light-flashes, and impact generated secondary ejecta particles (A. Mocker, *et al.*, *Planetary and Space Sci.*, submitted, 2012; K. Drake, *et al.*, *Planetary and Space Sci.*, submitted, 2012; A. Collette, *et al.*, *Planetary and Space Sci.*, submitted, 2012).

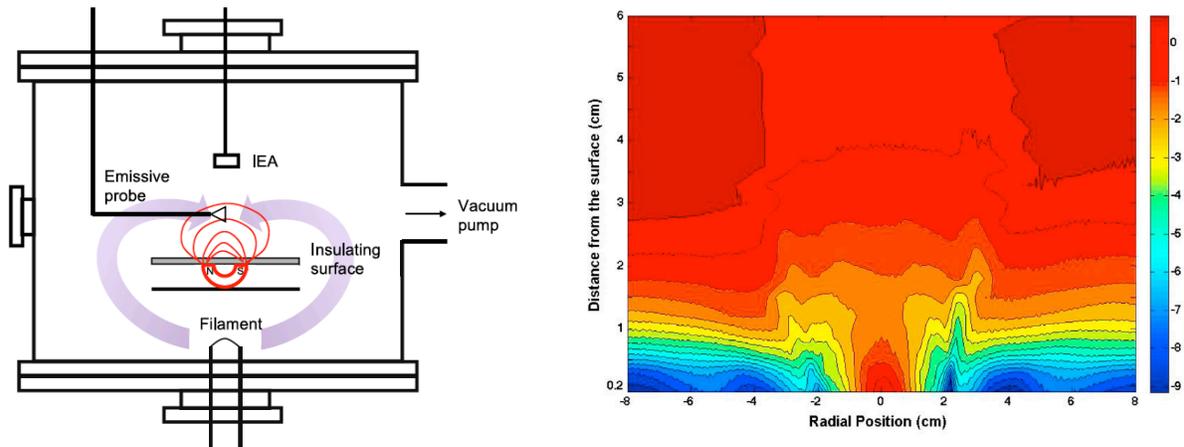


3D reconstruction of an impact crater shown in b and c with the depth profile measured from the cross section. Notice the two depth profiles are well matched. b) Cross section of the crater viewed at a  $52^\circ$  angle. c) Undamaged view of the crater with its visible interior. d) Cross section of an 'anomalous' crater. e) Same crater as in d, interior is not visible. f) 3D reconstruction with depth profile overlaid. The stereoscopic reconstruction cannot recover the concave profile.

## Small-scale Laboratory Experiments

We continued our studies of the plasma interactions with a magnetic dipole field at an insulating surface in order to understand the effect of crustal magnetic anomalies on the solar wind–lunar surface interaction. We have completed a series of experiments, and measured the potential distribution showing a non-monotonic sheath above the surface and strong variations on the surface along the axis of the dipole field. The surface near the center of the dipole was charged more positively by ions as the electrons are magnetically shielded away. A potential minimum was found in the shielding region between the surface and the bulk plasma due to collisional and magnetic mirror trapping effects. Potential variations on the surface are the result of the inhomogeneity of the dipolar field, showing an enhancement of the electric field at the cusps. Enhanced electric fields in the regions of magnetic anomalies on the lunar surface may enhance the transport of small-sized charged dust particles, possibly explaining the formation of the lunar swirls (Xu *et al.*, *J. Geophys. Res.* **117**, A06226, 2012)

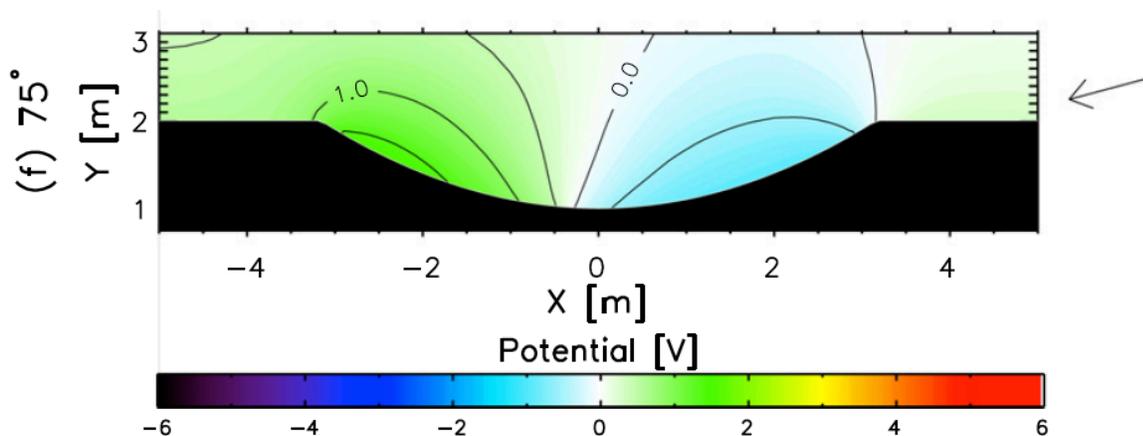
We have also completed a series of experiments to study the properties of photoelectron sheaths, and developed the diagnostic tools to measure the electron density and temperature in this dilute plasma (A. Dove *et al.*, *Phys. Plasmas*. **19**, 043502, 2012).



The schematic drawing of the experimental setup and the measured potential contours above the surface along the magnetic dipole axis. Colors represent potentials in volts.

## Theory Support

Computer simulation efforts continued to address our small-scale laboratory experiments. In addition, we focused on the dayside near-surface lunar plasma environment, which is electrostatically complex, due to the interaction between solar UV-induced photoemission, the collection of ambient ions and electrons, and the presence of micron and sub-micron sized dust grains. Further complicating this environment, although not well understood in effect, is the presence of surface relief, typically in the form of craters and/or boulders. It has been suggested that such non-trivial surface topography can lead to complex electrostatic potentials and fields, including “mini-wakes” behind small obstacles to the solar wind flow and “supercharging” near sunlit-shadowed boundaries. We have presented the first set of results from a three-dimensional, self-consistent, electrostatic particle-in-cell code used to model the dayside near-surface lunar plasma environment over a variety of local times with the presence of a crater. Additionally, we used the particle-in-cell model output to study the effect of surface topography on the dynamics of electrostatic dust transport, with the goal of understanding previous observations of dust dynamics on the Moon and dust ponding on various asteroids (Poppe *et al.*, *Icarus* **221**, 134-146, 2012). We are continuing to refine these codes to enable the inclusion of surface experimental packages, and/or landing spacecraft and their interactions with the lunar UV and plasma environment.



The electric potential above a crater on the surface of the Moon for a series of solar zenith angles zoomed into the near-crater region for clarity. Over-plotted are contour lines at 0.5 V intervals. The arrow along the right-hand side denote the incoming direction of solar UV radiation and the solar wind.

### **3. 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 LP Electron Reflectometer reported large negative surface potential over the sunlit side of the Moon, contradicting all theoretical expectations. Recently developed theoretical and simulation models suggest the formation of a 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. Poppe graduated in 2011, and now is a postdoc with the DREAM Team at UC Berkeley.

#### **LUNAR and CCLDAS**

Doug Curry (LUNAR) is leading an effort to develop a new generation of corner-cube retroreflectors for laser ranging. He brought a sample reflector to the CCLDAS dust accelerator in March 2011 to investigate the effects of hypervelocity dust impacts on the optical properties of the sample. This exploratory experiment will likely be followed up with a systematic study of crater-forming impacts on optical devices.

#### **Brown U. Team and CCLDAS**

Initial experiments to investigate space weathering due to dust impact were done in the spring of 2012. Basalt samples were exposed to hyper-velocity ( $> 1$  km/s) iron dust impacts to identify changes in their reflectance spectra. A follow up series of 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**

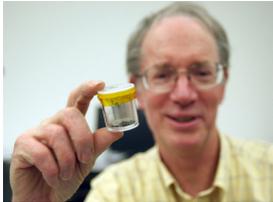
CCLDAS closely collaborates with the dust group at the Max-Planck-Institute for Nuclear Physics, Heidelberg, and the University of Stuttgart, Germany, both members of the German Lunar Science Institute. CCLDAS greatly benefited from these collaborations in the development of our dust accelerator facility. We are establishing a common data management system for dust impact studies, and plan on scheduling parallel complementary experiments. 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. Dr. Anna Mocker (U. of Stuttgart) is a visiting scholar at CCLDAS for the period of 8/2011 - 04/2014. Her first year at CCLDAS was supported by DLR, Germany. CCLDAS graduate student Anthony Shu (supported by NLSI) spent 3 weeks at the MPI-K dust accelerator. Initiated by CCLDAS and the Institute for Space Systems, the University of Colorado and the University of Stuttgart signed a Memorandum of Understanding to set the framework for collaborations in lunar and space research.

## 4. EPO Highlights

### New Media Practitioners Professional Development Workshop

The 2012 New Media Practitioners Professional Development Workshop on the **Future Exploration of the Moon and Small Bodies** (Boulder, July 20–22, 2012) brought seventeen bloggers, podcasters, and other science communicators to CCLDAS for a two-day intensive workshop with space scientists. The workshop was a collaborative professional development opportunity for attendees to learn about current issues surrounding future exploration of the Moon and other small bodies in our Solar System.

Workshop web page: [http://lasp.colorado.edu/home/ccldas/files/2012/07/CCLDASWorkshopSUMMARY\\_2012.pdf](http://lasp.colorado.edu/home/ccldas/files/2012/07/CCLDASWorkshopSUMMARY_2012.pdf)



Moon dust in my hand .... a levitating experience, by 'blogger' AstroBob  
<http://astrobob.areavoices.com/2012/07/22/moon-dust-in-my-hand-a-levitating-experience/>

### Junior Aerospace Engineering Project

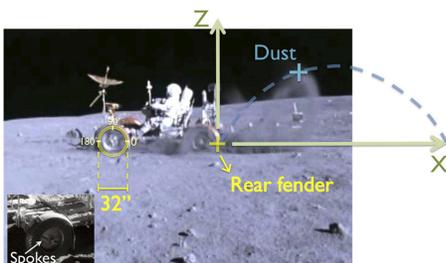


Robotic search for 'ice' in the CCLDAS moon garden ....

The 2012 Junior Aerospace Engineering Project **LEGO Lunar Rovers: Mission to the Moon** (July 9–27, 2012) brought ten underserved high-school students to CCLDAS for a three-week program. The program was a collaborative opportunity for students to learn about current issues surrounding past and future exploration of the Moon, engineering design/CAD concepts, computer programming skills, and basic lunar and space physics concepts. The students worked in small teams to design LEGO lunar rovers, create CAD models, and program their rovers to complete a series of tasks on a simulated lunar surface. They were also exposed to real-world science applications and research during presentations from a number of speakers who are working on current lunar missions and programs. Web page: [http://lasp.colorado.edu/home/ccldas/files/2012/12/CCLDAS\\_LEGO\\_SUMMARY\\_2012.pdf](http://lasp.colorado.edu/home/ccldas/files/2012/12/CCLDAS_LEGO_SUMMARY_2012.pdf)

### Classroom activity Development

Selected video images from the Apollo 16 mission were analyzed to follow the motion of dust clouds kicked up by the wheels of the Lunar Roving Vehicle (LRV). Applying the equations of ballistic motion, both the velocity of the dust and the gravitational field strength at the lunar surface can be estimated. Such exercises can be utilized when discussing ballistic trajectories and angular motion in a high school or introductory level college physics class (H.-W Hsu and M. Horányi, *American Journal of Physics*, **80**(5), 452, 2012).

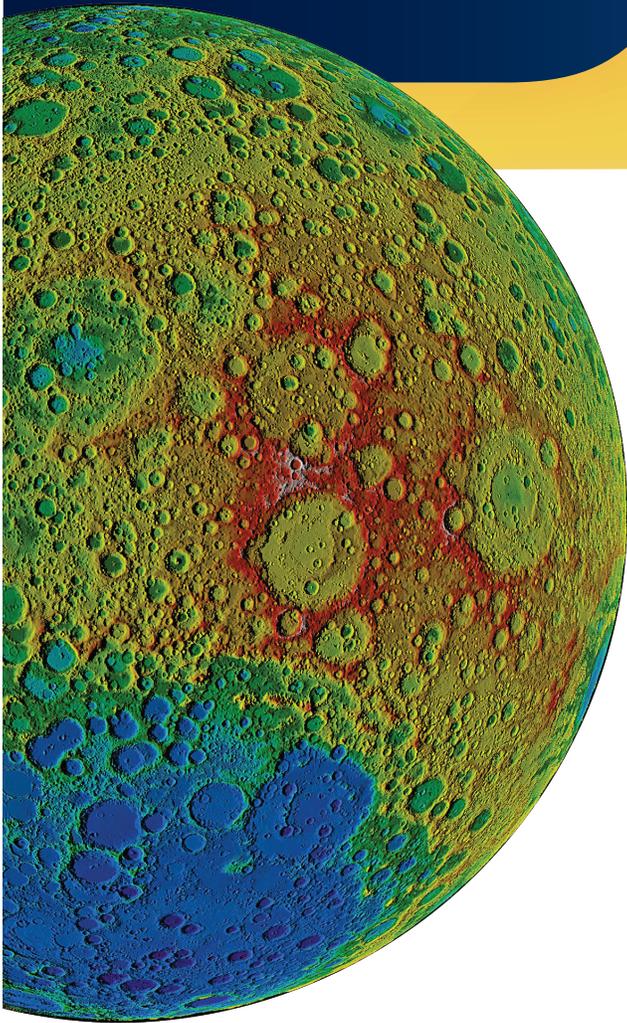


Analyzing the 'rooster tails.' The 2D coordinates system is centered and fixed at the rear fender of the Apollo 16 LRV. The location of the top of the dust cloud is marked by a cross. The front wheel and the rotation angle of its spoke are also shown. The spokes are shown in the lower-left inset image.

# Lunar University Network for Astrophysics Research (LUNAR)



*Principal Investigator:  
Jack Burns (U. Colorado)*



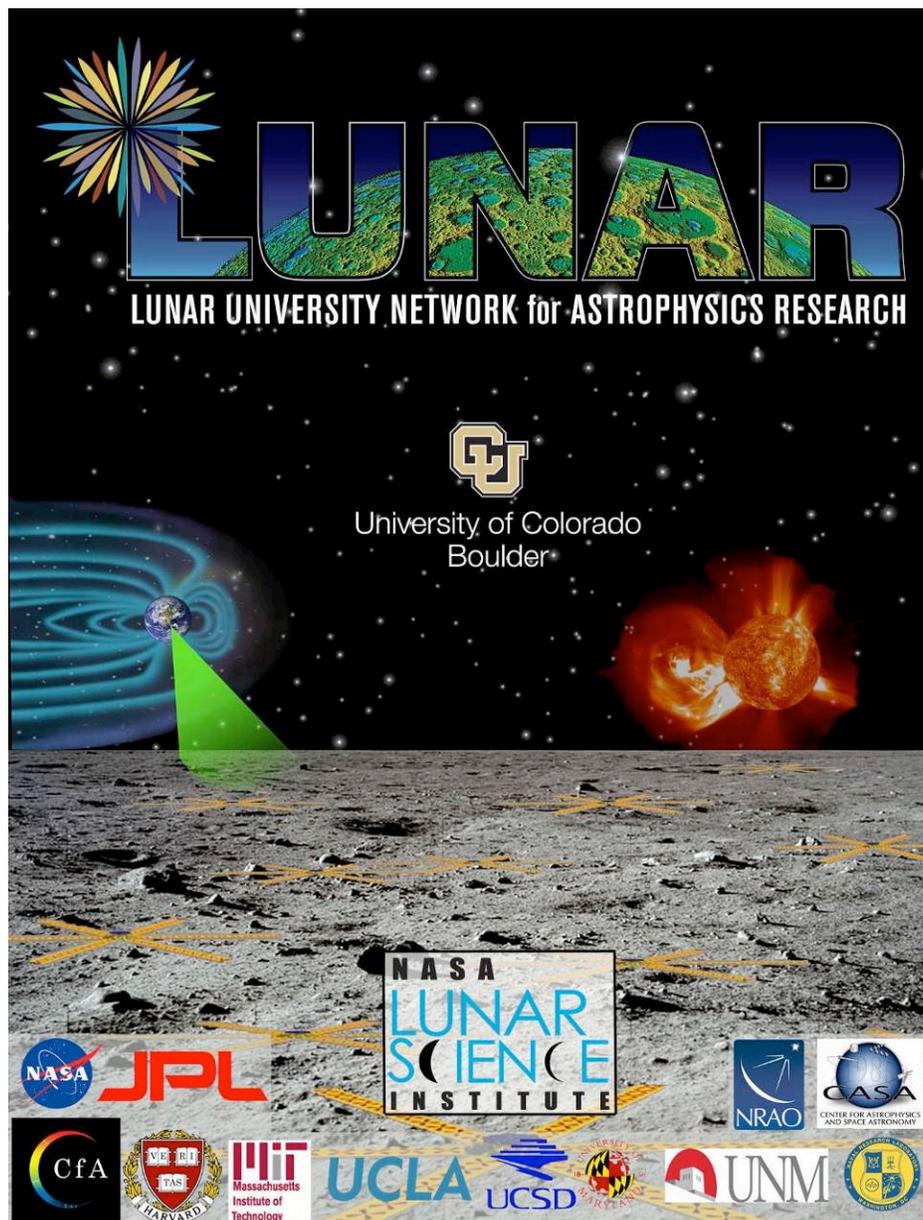
# Lunar University Network for Astrophysics Research: Year 4 Report to

## The NASA Lunar Science Institute

February 15, 2013

*Principal Investigator:* Jack Burns, University of Colorado Boulder

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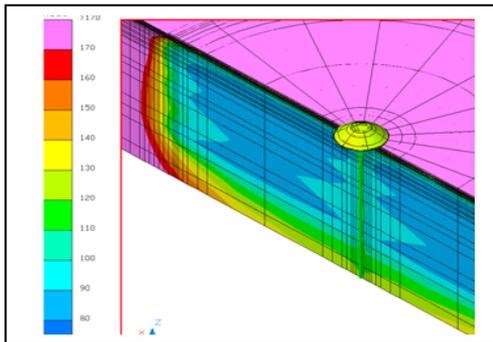
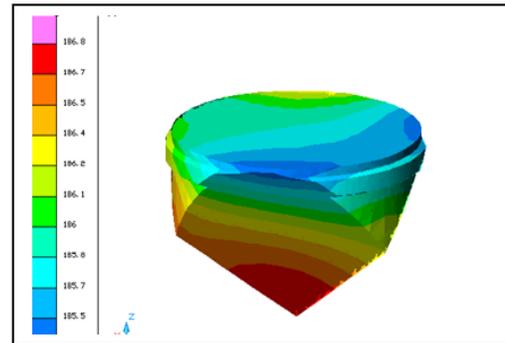
## Overview of LUNAR

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), and Heliophysics.

### Lunar Laser Ranging

#### Opto-Thermal Simulation

The purpose of the Opto-Thermal Simulation is to evaluate the heating effects of the solar illumination, and then incorporate these heat loads into the energy exchanges between the Cube Corner Reflector (CCR) and space, between the CCR and the sun shade and the heat inputs from the sun and the thermal radiation from the regolith. This simulation has been developed at U. Maryland in connection with INFN-LNF in Italy. Fig. 1 illustrates a typical temperature distribution in the CCR, and Fig. 2 a computation of the regolith temperature since the radiation from the regolith affects the LLR Retroreflector.



Within the past year, the simulation has been refined to include a number of additional effects and to improve the running speed, since the run for a single set of the twelve relevant parameters requires about two days with detailed operator involvement. In addition, new thermal coatings for the sunshade and for the housing have been incorporated.

#### Optical Material Effects

The properties of the optical material for the CCR have been studied. Interferograms of the optical behavior of the CCR have been made and the simulation upgraded to incorporate these in evaluating the performance, in the form of the signal received on earth.

#### Velocity Aberration

Since the retroreflector on the Moon is moving with respect to the observatory on earth, the laser return arrives offset from the observatory. As a result, the angles between the back faces of the CCR must be offset to send some of the energy back to the observatory. This software has been developed and is being refined.

#### Stepped Sunshade:

Reflections of the incoming sun light can be reflected from the interior of the sunshade. In order to reduce this effect, a “stepped” design has been simulated. It reduces the solar energy striking the CCR by 40%. In order to evaluate the actual effect, such a sunshade has been fabricated (Fig. 3). This will be tested in the Satellite/lunar laser ranging Characterization Facility (SCF) in Frascati, Italy late this spring. These tests will identify any un-modeled effects to allow the simulation to best represent the real world.

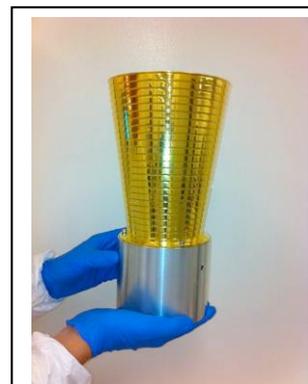


Figure 3 Retroreflector Conceptual Design, especially addressing stepped sunshade, for SCF testing.

### **Pneumatic Drilling to Thermally-Anchor CCR:**

In order to deploy the next-generation CCR in a manner that the thermal changes in the support of the package do not change the position at the tens of microns level, the package must be anchored into the regolith at a depth of nearly a meter. Drilling in this manner has traditionally been very difficult during the Apollo missions. However, HoneyBee Corp. funded by LUNAR has developed the “pneumatic” drilling technology. This has been tested in compacted regolith simulant in vacuum and at 1/6 g.

## **Low Frequency Cosmology and Astrophysics (LFCA)**

### **Theoretical Tools and Science Development**

Furlanetto has continued to study theoretical models of the first galaxies. As these are the most likely sources for the photons that drive the neutral hydrogen 21 cm signal, understanding their properties is crucial for predicting and interpreting that signal from future lunar observatories. Furlanetto and his group focused on several aspects of these sources, including the relative velocity of dark matter and baryons, the internal structure and star formation laws of the most distant known galaxies (at redshifts  $\sim 6-8$ ), their contribution to the near-infrared background, and the development of a “standard model” for cosmic reionization based on *Hubble Space Telescope* observations. The latter was done in conjunction with the UDF12 team (PI: R. Ellis). Pritchard and Loeb, in collaboration with A. Liu and M. Tegmark, explored details of foreground removal for global 21 cm experiments from a starting point of building a maximum likelihood estimator for the signal that assumed nothing about the signal itself. This research complements earlier LUNAR work led by Harker, Burns et al. that approached the same problem from a Bayesian perspective that assumed a detailed signal model. This work resulted in a publication that demonstrated a) the feasibility of removing foregrounds in realistic situations, and b) the importance of making use of spatial information for the foreground removal. Loeb and Furlanetto published a new textbook on *The First Galaxies in the Universe* (540 pages) that summarizes the motivation and scientific background for a lunar radio telescope in observing Cosmic Dawn. Using one-dimensional radiative transfer calculations, CU grad student Mirocha, Burns et al. investigated the discrepancies in gas properties surrounding model stars and accreting black holes that arise solely due to spectral discretization. Even in the idealized case of a static and uniform density field, it was found that commonly used discretization schemes induce errors in the neutral fraction and temperature by factors of two to three on average, and by over an order of magnitude in certain column density regimes. A method for optimally constructing discrete spectra was developed, and it was shown that, for two test cases of interest,

carefully chosen four-bin spectra can eliminate errors associated with frequency resolution to high precision.

### Antenna Technology Development

Stewart and Hartmann deployed a prototype lunar surface antenna at the JVLA site in New Mexico. This test was the first with the lunar surface antenna on a dry desert soil, a far more realistic lunar analog than used for previous testing. They found good agreement between numerical simulations and measurements of the electromagnetic properties (gain, response pattern, and feedpoint impedance). Bradley developed a new approach to receiver calibration for a switching radiometer. It makes use of the fact that the low noise amplifier's scattering and noise parameters are invariant to the network's input impedance. The calibration

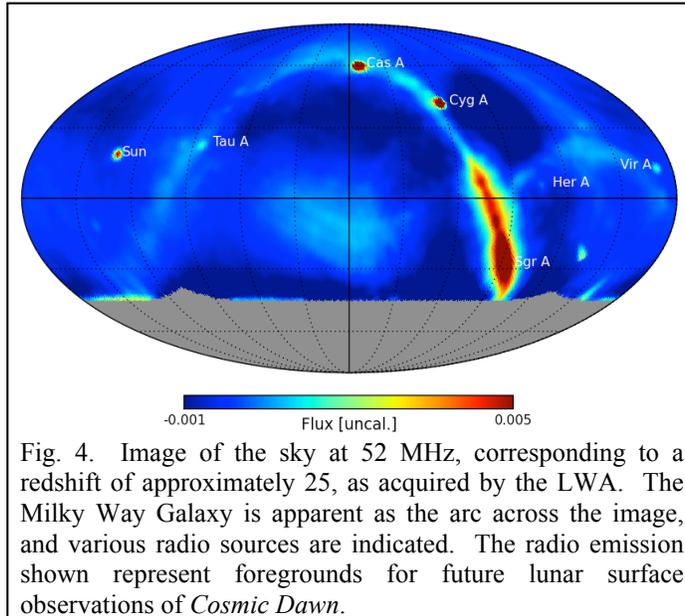


Fig. 4. Image of the sky at 52 MHz, corresponding to a redshift of approximately 25, as acquired by the LWA. The Milky Way Galaxy is apparent as the arc across the image, and various radio sources are indicated. The radio emission shown represent foregrounds for future lunar surface observations of *Cosmic Dawn*.

procedure, which utilizes both high precision *a priori* laboratory measurements of the circuit temperature-dependent parameters together with real-time monitoring of the circuit's physical temperature, was designed from first-principles. A project report was written detailing the calibration procedure. Jones investigated whether a lunar surface radio antenna, useful for studying either the global 21 cm signal or the lunar ionosphere, could be deployed while a lander was in its descent phase, before reaching the surface. The initial assessment was that this approach is promising, but “sand blasting” by the lunar regolith has yet to be considered fully. Taylor and colleagues took advantage of the completion of the first station of the Long Wavelength Array to investigate imaging the sky at low frequencies (10–88 MHz) (Fig. 4). This work resulted in a better characterization of the emission of the galactic background, strong radio sources and sources of transient emission. These observations will inform the design of future instruments.

### LUNAR Simulation Laboratory

The LUNAR Simulation Facility at Colorado is used to test the effects of the harsh lunar environment on materials and hardware. LUNAR team members recently finished construction on a second thermal-vacuum chamber that contains a bed of JSC-1 lunar simulant for a more realistic representation of the lunar surface. Copper-coated Kapton was thermally cycled for one month, with each 24 hour cycle representing a lunar day or night. The Kapton showed greater thermal variation than pieces tested in the original vacuum chamber, possibly due to the simulant regolith deforming with the Kapton and maintaining greater thermal contact than the aluminum table.

### Earth-Moon L-2 Mission Concept

Burns, Kring (LPI), Lazio, & Kasper developed a concept for a crewed mission to the Earth-Moon L-2 point in which the astronauts would tele-operate a lunar surface rover or rovers. These lunar surface assets could be used to collect lunar samples for a sample-return mission, and deploy lunar surface antennas to study the global 21 cm signal.

## Radio Heliophysics

Heliophysics Key Project Year Four Goals were divided between (1) Studies of fundamental low frequency radio science, (2) Development of new techniques to measure interplanetary dust using the frequency spectrum of fluctuations induced by dust impacts, and (3) general support of the NLSI and LUNAR projects.

### Nanodust Impacts

Recent work has highlighted the ability of electric field antennas on spacecraft to indirectly characterize dust by detecting the expanding plasma produced when a high-speed dust grain impacts the spacecraft. LUNAR post-doc Zaslavsky derived analytic expressions for the time-dependent voltage waveform measured by an electric field antenna embedded in the expanding plasma plume produced by a hyper-kinetic dust impact. These predictions were compared with observations of the waveforms produced by dust impacts detected with the WAVES/TDS experiment on the STEREO spacecraft. Zaslavsky found that the analytic predictions successfully matched the relative strength of the signals seen by the three different antennas on each spacecraft, and the total strength proportional to the product of dust grain mass and impact velocity.

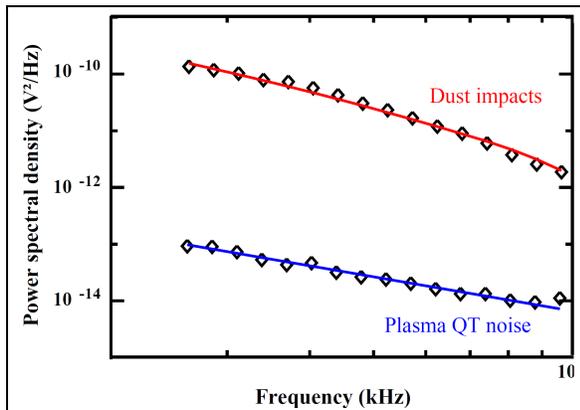


Fig. 5: Power spectrum measured by *STEREO A*. The upper spectrum is typical of dust measurement, whereas the lower one corresponds to the plasma quasi-thermal noise measurement. The lines correspond to the best fit, in case of dust (red) and plasma thermal noise (blue).

LUNAR postdoc Le Chat used the analytic equations for the time-dependent voltage waveform in Zaslavsky et al. (2012), and derived expressions for the frequency dependent signature of a dust impact. Fig. 5 compares the typical spectrum of low frequency fluctuations in the solar wind (blue) with the spectrum recorded as a dust particle struck the spacecraft. Overall, the functional form of the predicted signal matched the observations from the spacecraft very well. Le Chat's results are significant because they allow us to use the STEREO spacecraft observations to derive continuous and unbiased measurements of the variability of nanodust flux in interplanetary space. These measurements were then used produce a more accurate estimate of the mass distribution of interplanetary dust than has been published previously, using a model that required fewer assumptions than previous works.

The Radio Heliophysics project focuses on various aspects of radio observations of particle acceleration, in particular, low-frequency (<10 MHz) radio emissions produced in the outer corona and heliosphere by flare- and shock- accelerated electrons. Such radio bursts have never been imaged, because their frequencies are blocked by Earth's ionosphere, and because no adequate radio interferometric array has been assembled in space to make such imaging observations. Thus a key goal has been to study implementation an aperture synthesis array on the lunar surface to observe the low-frequency radio bursts. This observatory, which we call the Radio Observatory on the Lunar Surface for Solar Studies (ROLSS), has been studied

extensively. With ~50 monopole antennas covering a total diameter of order 1 km, it is a project that can be implemented with a lunar lander of moderate capabilities.



Fig. 6. (Left) GSFC summer interns with cross bow-launched anchor deployer. (Right) Inflatable tube with dipole antennas; the tube has been deflated after a successful deploy.

The ROLSS antennas are planned to be deposited on polyimide film that would be unrolled on the lunar surface. To facilitate that effort, LUNAR team members at GSFC focused on various aspects of a pathfinder mission for ROLSS, that would test antenna design and other aspects of ROLSS. The ROLSS pathfinder (ROLSS-P) would be a small package (volume of order 0.01 m<sup>3</sup>) that could be the science payload on a small lander or carried as a secondary payload. Deploying the 1-3 antennas comprising the sensing elements of ROLSS-P could be done with a variety of

techniques. LUNAR has tested hardware for launched anchor deployment and inflated tube deployment. Fig. 6 shows examples of the hardware being tested. Elements of deployment and inflation testing were performed by interns as their summer 2012 project at GSFC. From these tests, we have derived a much better understanding of the primary risks for each type of deployment and the terrains for which they work the best.

### Inter-Team Collaborations

The LUNAR team worked with *Kring* (CLSE) to develop the concept of an Earth-Moon L2 mission in which astronauts would control lunar surface assets to pursue simultaneously high priority science goals from both the Planetary Sciences and Astronomy Decadal Surveys.

The LUNAR team worked with *Farrell* (DREAM) to refine the science case for a lunar surface radio antenna to study the ionized lunar atmosphere.

The LUNAR team worked with *Farrell* (DREAM) in searching for radio emissions from extrasolar planets, which would be an important secondary scientific goal for a future lunar radio telescope.

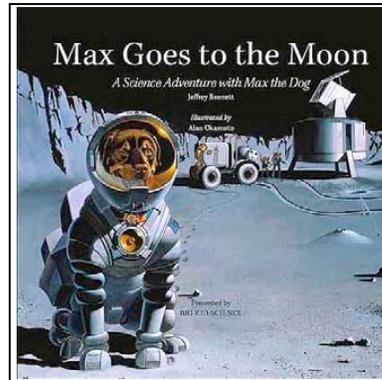
### Education & Public Outreach (EPO)

The LUNAR team has a diverse and aggressive EPO effort aimed at enhancing the awareness and knowledge about the Earth-Moon system. In Year 4, we completed our signature EPO effort with the premier and national distribution of our children’s planetarium show. LUNAR also used the Solar Eclipse of the Sun in May of 2012 to increase public awareness of science and NASA’s role.

Our children’s planetarium program is based on the award-winning book, “Max Goes to the Moon” by local Boulder author Dr. Jeffrey Bennett. NASA astronaut Alvin Drew played a role

in the development of this show. On Drew's mission to the International Space Station he had the opportunity to read the story "Max Goes to the Moon" to the children of Earth. 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 Lunar Science Forum. The feedback we gathered resulted in significant improvements to the show. In March of 2012 Astronaut Alvin Drew came to Fiske Planetarium to help launch this program at our national premier. "Max" is now playing at 6 planetariums across the country and more are in the process of acquiring it. It has been promoted by the International Astronomical Union.

In May 2012 an annular solar eclipse was visible in the western half of the US. LUNAR partnered with the CCLDAS team led by M. Horanyi to take over the university football stadium

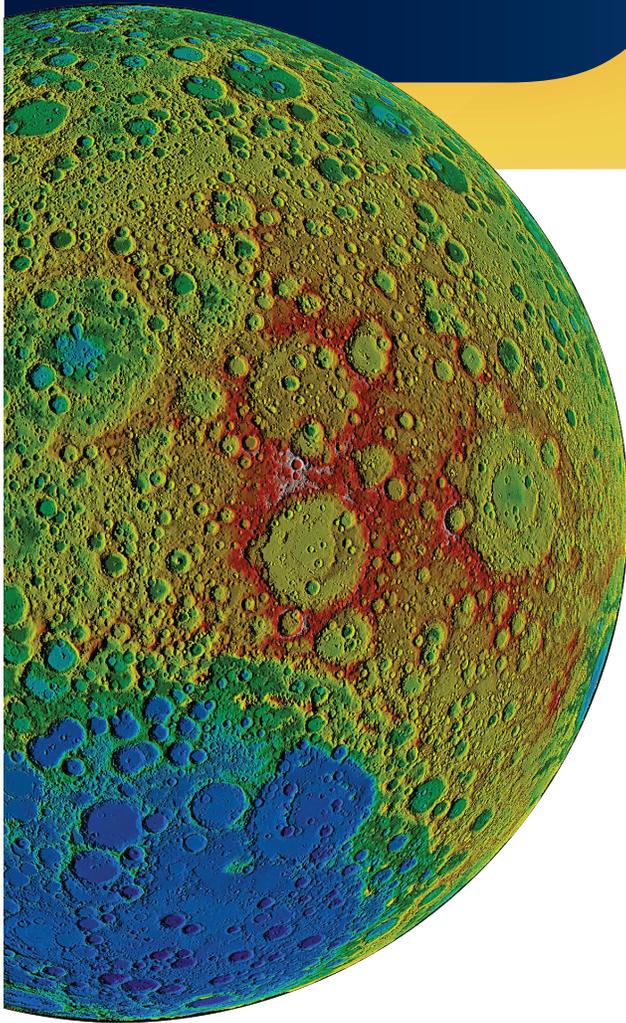


(Folsom Field). We also distributed roughly 40,000 eclipse glasses to K-12 students. **Our event became the largest crowd on record in one place to watch a solar eclipse.** Roughly 10,000 people attended this event. It was broadcast extensively on TV including ABC World News Tonight. We had NASA and Fiske videos and animations playing on the stadium's "Big Screen Video" that explained eclipses and also highlighted NASA missions that have enhanced our knowledge of the Earth-Moon system.

# Center for Lunar Science and Exploration



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

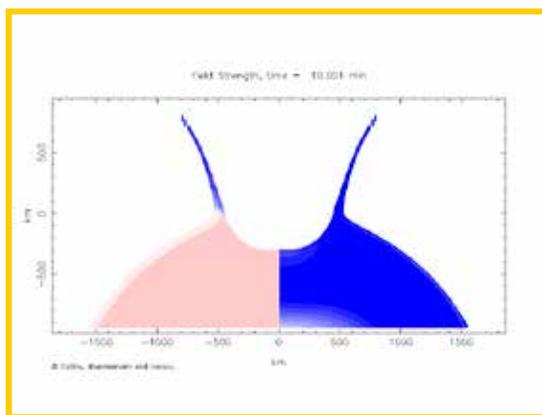


## NLSI Yr4 Annual Report

### 1. Team Project reports

At the core of the Center’s activities is a series of studies to test concepts associated with the collisional evolution of the Moon and, in particular, from the time of accretion to the end of the basin-forming epoch. We investigated the formation of the oldest and largest basin on the Moon, the South Pole-Aitken basin, using a computer hydrocode (Potter et al., 2012a). That work suggested the basin was produced by a 170 km diameter asteroid moving at about 10 km/s. Interestingly, in a parallel study that examined surfaces related to the South Pole-Aitken basin and younger basins, we detected a shift in the size distribution of impactors between the formation of the South Pole-Aitken basin and that of the Nectaris basin (Marchi et al., 2012). That suggests the South Pole-Aitken basin was produced by a remnant of accretion, while Nectaris and younger basins were produced during the period of late heavy bombardment. That work also suggests the South Pole-Aitken impact was produced by a relatively slow impactor (~10 km/s), before impact velocities doubled during the latter part of the basin-forming epoch. That increase in velocity is consistent with a population of asteroids that were dynamically excited by a shifting of Jupiter’s orbit that we had previously inferred (e.g., Strom et al., 2005).

We integrated our studies of the size distribution of craters (Marchi et al., 2012) with an assessment of the ages of the youngest basins and measurements of the highly siderophile signatures of impactors derived from lunar samples (Morbidelli et al., 2012). That led to a calibrated timeline for the first billion years of lunar bombardment that suggested that the South Pole-Aitken basin was produced 4.3 Ga or before. Thus, we have a prediction of the age that could be found once samples of South Pole-Aitken basin are returned to



Earth. Furthermore, the model of Potter et al. (2012a), shows that the impact melt produced by the South Pole-Aitken basin-forming event was dominated by mantle and lower crustal lithologies, which provides critical compositional constraints needed to identify South Pole-Aitken basin samples suitable for geochronology. We are continuing to explore the implications of that melt composition with calculations of the chemical and mineralogical evolution of that melt (Hurwitz and Kring, 2013).

**Figure 1.** Time step in the hydrocode simulation of the South Pole-Aitken basin-forming impact event. The code allows us to keep track of the properties and distribution of material affected by the impact event. Potter et al. (2012a)



Modeling of basin-forming events (Potter et al., 2012b) indicates that the thermal state of the Moon affects the diameters of basins and the dimensions of subsurface bulges of the crust created by those events. Furthermore, we have shown (Potter et al., 2013a, submitted) that the amount of structural uplift in a basin center is attenuated as a function of depth in a predictable way. Both of those results are playing very important roles in the ongoing analysis of the new GRAIL data.

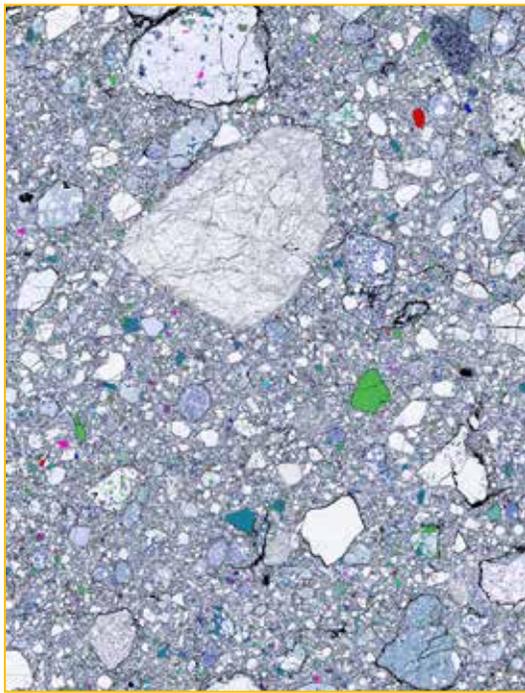
The Orientale basin is the last of the basin-forming impact events. It is an immense 930-km diameter structure on the western limb of the Moon and nearly perfectly preserved. Thus, it has been a classic site for studies of the basin-forming geologic processes. This year we examined the basin in two ways. We used LOLA data to examine the topography across the basin rings and then used a model to determine if they were produced by immense normal faults (Nahm et al., 2013, in press). The modeling suggests the Cordillera and Outer Rook rings are, indeed, produced by normal faults with displacements of 0.8 to 5.2 km and a depth of faulting between 19 and 37 km. This work favors models of basin-formation similar to those inferred from the Chicxulub impact basin on Earth and seriously undermines several other basin-forming models. At the same time, we simulated the Orientale impact event using a hydrocode to determine basin properties that cannot be inferred from the surface expression of the basin, including the impact energy, impactor size, transient crater size, excavation depth, and impact melt volume (Potter et al., 2013b, submitted).

After the Moon accreted, there appears to have been a significant decline in the impact flux between  $\sim 4.4$  and  $\sim 4.1$  Ga because there are very few impact ages within that interval. This is true both in our analyses of the Moon (e.g., Swindle et al., 2012) and those of asteroids (e.g., Swindle et al., 2013, in press) that are relicts of minor planets that now populate the main asteroid belt and sometimes pass through near-Earth space. That is not to suggest there were no impacts in that interval, just a smaller number. Indeed, using new techniques developed as part of this project, our team and its international partners (Grange et al., 2011; Nemchin et al., 2012; Grange et al., 2013) have detected several impacts occurring in the 4.4 to 4.1 Ga interval.

Soon thereafter, however, there seems to be a sharp rise in the impact flux that produced a large number of impact ages  $\sim 4.0$ -3.8 Ga on the Moon and  $\sim 4.0$ -3.6 Ga in the main asteroid belt. That enhanced flux is often called the late heavy bombardment or lunar impact cataclysm.

We have tested the lunar cataclysm hypothesis repeatedly and found that there truly was an increase in the impact flux that produced, for example, a series of distinct impact melts at the Apollo 16 landing site in a very short amount of time  $\sim 3.9$  Ga (e.g., Niihara et al., 2013). Moreover, those impact melts were produced by different types of asteroids, each

of which left a distinct chemical fingerprint in the impact melts (e.g., Liu and Walker 2013).



In a spectacular study, we also found mineralogical relicts of the impactors hitting the Moon at the end of the basin-forming epoch (Joy et al., 2012). The result was confirmed in multiple samples from the Apollo 16 site. Moreover, we examined regolith samples that were consolidated after the basin-forming event and found that the population of impactors appears to become more diverse as the solar system ages. We are continuing to probe that result with additional studies of samples from other Apollo landing sites.

This year we also published a study of the basalts at the Apollo 15 landing site (Taylor et al., 2012) and have in press a comparative study of basalts and impact melts at the Apollo 14 landing site (Fagan et al., 2013, in press).

**Figure 2.** An example of the new analytical mapping techniques that were developed through our NLSI program to detect mineralogical relicts of the impactors that re-shaped the Moon 3.5 to 4.0 billion years ago. (Joy et al., 2012).

Our integration of science and exploration objectives produced two global lunar landing site studies (Flahaut et al., 2012; Kring and Durda, 2012) that identified some fascinating exploration targets for future robotic and human missions. Among them is the Schrödinger basin. That site can provide access to samples that address the highest lunar science priorities (O’Sullivan et al., 2011).

For that reason, we initiated a series of more detailed studies of the basin that have revealed a spectacular array of outcrops suitable for collection and return to Earth. That includes a study that integrates an assessment of the major geologic features using LROC images with  $M^3$  spectroscopy (Kramer et al., 2013) and a detailed assessment of a crater that exposes fresh bedrock in the basin’s peak ring (Kumar et al., in press). Collectively, these studies suggest the Schrödinger basin is a very strong candidate for future sample return missions. In one of our latest studies, we propose the Schrödinger basin as the landing site for a mission concept (Burns et al., 2013) involving a robotic lander that can be tele-operated by crew on the Orion spacecraft at the Earth-Moon L2 position.



## 2. Inter-team Collaborations

We initiated our NLSI program with a planned collaboration with the NLSI team at the Southwest Research Institute. That has produced a super set of results in Yr4 of our project. As described in Section 1, Marchi et al. (2012) studied ancient crater populations on the Moon and discovered a shift in the size distribution that implies (a) that the South Pole-Aitken basin was produced during the accretional epoch and that (b) the impact velocity of asteroids doubled during the lunar cataclysm. That was followed by Morbidelli et al. (2012) which calibrated the impact flux during that interval of time and, among other results, predicts the age of the South Pole-Aitken basin is 4.3 Ga or older.

As the NLSI evolved, we identified several productive collaborations with other NLSI teams. In Yr4, we published a new geologic assessment of the Schrödinger basin (Kramer et al., 2013) with the NLSI team from Brown and MIT.

That basin has become an important focus of our studies, because it is a high-priority site suitable for important scientific and exploration objectives. Working closely with one of the NLSI teams at the University of Colorado, we developed a mission concept that explores Schrödinger basin using robotic surface assets and crew on the Orion vehicle at the Earth-Moon L2 position 60,000 km above the surface (Burns et al., 2013). Not only did we develop the mission concept together, but we also showed how geological and astrophysical objectives can be met using that same mission scenario. That type of synergy is creating a more efficient exploration path.

Finally, to further evaluate the exploration ISRU potential of Schrödinger basin, we initiated another collaborative study with the NLSI team at APL. That study is still underway, but we anticipate results in 2013.

We fostered international collaborations too, some of them with teams with formalized agreements with NLSI Central and some of them with teams that are working to establish formalized agreements with NLSI central. We collaborated with the PI of the Netherlands NLSI partner in a study of sites on the lunar surface that are suitable for studies of the lunar crust (Flahaut et al., 2012). We collaborated with the PI of the Canadian NLSI partner in the development and implementation of a Short Course and Field School at the Sudbury Impact Structure (October 2012). PI Kring also journeyed to Europe to give a keynote address in a lunar conference co-organized by the PI of the United Kingdom NLSI partner. We have also been developing rich collaborations with scientists in Australia. Those collaborations have been so productive that the team members involved submitted an application for a formal partnership between Australia and NLSI Central (which is currently being reviewed). These projects enriched our own team and, we hope, enriched the broader goals NLSI program.



### 3. EPO Report

**Strategy** – To 1) strengthen the future science workforce; 2) attract and retain students in STEM disciplines; and 3) develop advocates for lunar exploration. To accomplish these goals, the CLSE Team continued to conduct the High School Lunar Research Projects Program, facilitate the Traveling Exhibits Program for libraries, and collaborate with NLSI Central and other NLSI E/PO teams in engaging educators and the public.

**High School Lunar Research Projects** (<http://www.lpi.usra.edu/nlsi/education/hsResearch/>)

Through the High School Lunar Research Projects, teams of students from across the nation participate in authentic lunar research projects aligned with CLSE research objectives and NRC science priorities. NASA lunar scientists advise the students as virtual mentors. A panel of lunar scientists judge the research projects; posters from the four top-ranked teams are presented at the annual NASA Lunar Science Forum, and the top-ranked team attends the Forum. The program provides a standards-based, data-rich, first-hand science experience that supports the high school curriculum, enhances skills and proficiency in science, and strengthens the pipeline by identifying pathways for students interested in higher education science studies.



*The winning team from Chenango Forks High School present their poster at the Forum where they are encouraged to talk with a broad range of lunar scientists.*

Nine high schools are participating in our Yr4 program. To date, 232 students (36 teams) and 20 teachers have participated. Of the 20 individual schools involved, 13 serve significant underserved or underrepresented populations. Six more serve rural or urban populations. The project has resulted in 6 posters being presented at professional science organizations and 15 student posters being presented at the annual Forum.

**Traveling Exhibits for Libraries** (<http://www.lpi.usra.edu/nlsi/education/exhibits/>) -

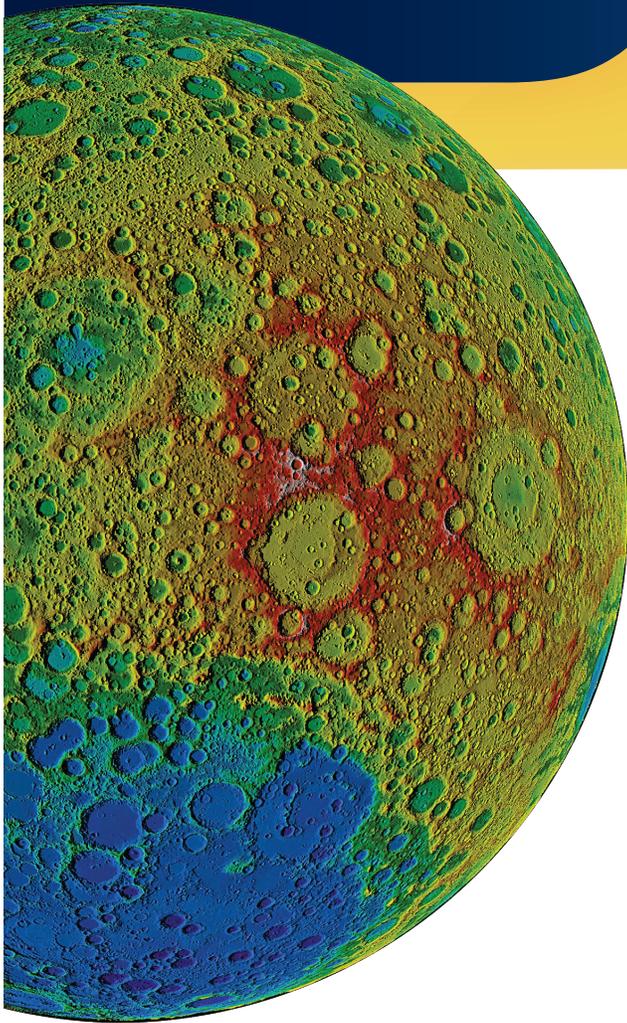
The CLSE traveling exhibits provide libraries with resources through which they, in turn, engage the public in CLSE and NLSI lunar science and exploration. Seven traveling exhibits currently are in circulation, advertised through the LPI Explore Library Program, NASA’s Museum Alliance and the American Library Association. To date, the exhibits have been viewed by approximately 120,000 visitors in over 30 unique locations including libraries, science centers, observatories, and planetariums.

**Collaborative Activities** - Reaching out to the Public, including serving on the InOMN team, hosting 300 InOMN participants, and facilitating a family event at the 2<sup>nd</sup> Annual Lunar Highlands Crust Conference in collaboration with the GRAIL Mission Team. Collaborating on educator workshops, including co-facilitating the annual Unknown Moon high-school educator workshops with the APL team and supporting numerous week-long summer LRO educator workshops. Supporting informal educator efforts including NLSI’s Center for Lunar Origins and Evolution (CLOE) two-day librarian workshops, sharing of lunar exhibits with CLOE libraries and other NLSI E/PO teams, and disseminating resources of NLSI teams (e.g., Max Goes to the Moon).

# Dynamic Response of the Environment at the Moon (DREAM)



*Principal Investigator:  
William Farrell (GSFC)*



# DREAM PY4 Annual Report

## 1.0 Overview

The surface of the Moon is constantly bombarded by solar energy and matter, by impactors (large and small), and by galactic cosmic radiation. These oxide-rich, volatile-encrusted interfaces respond to this incident surface energy by emitting neutral gases, by ejecting particulates, and possibly by converting implanting solar wind protons into hydroxyls and water (Figure 1). The conventional wisdom is that these exposed bodies are in a vacuum and are effectively inert or ‘dead’. However, at the microscopic level they are in fact quite animated by the activating energy in this space environment. DREAM examines the interaction of solar energy and matter with the exposed lunar regolith, advancing the understanding the effect that incident plasma, photonic and charged particle radiation, and impactors have

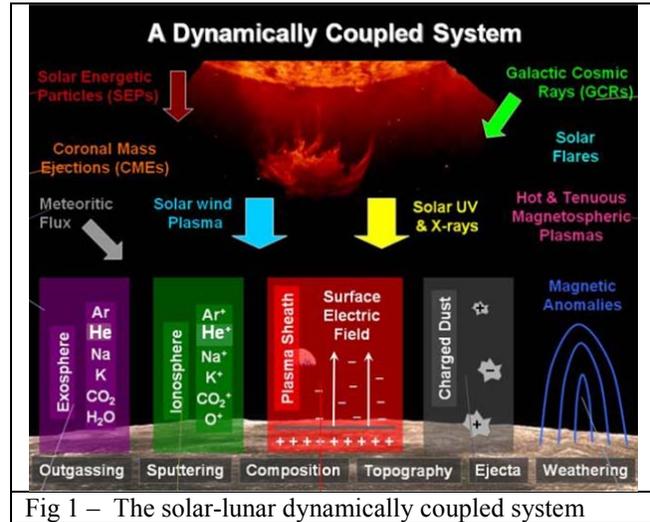


Fig 1 – The solar-lunar dynamically coupled system

on the surface itself and on human-made objects placed on the surfaces. DREAM results not only advance the planetary cross-cutting themes of volatiles and chemical/physical processes but are applicable to human exploration by filling-in strategic knowledge gaps in radiation, resources, plasma, and dust/regolith. We address notable DREAM-Year 4 achievements below.

**1.1.Exospheres.** DREAM’s exosphere team devote considerable resources for further understanding the origin of the lunar water/OH veneer detected at mid-latitudes by IR sensing systems [Pieters et al., 2009; Clark et al., 2009; Sunshine et al., 2009]. Specifically, DREAM investigated the possibility that some of this water may be a redistribution of the existing icy-regolith known to be located at the bottom of polar craters. While these regions are shadowed and cold, the crater surfaces can still be energized by the space environment (solar wind ion entry, electron stimulated desorption, Lyman-Alpha desorption, and impact vaporizing). A key finding is that water atoms can indeed be ejected from the craters to mid-latitudes by impact vaporization events, but the amount of water ejected is simply not enough to account for the IR absorption features near 2.8 and 3 micron [Farrell et al., 2013].

Hurley also examined the solar wind fluence over lunation time scales and determined the solar wind ion implantation residency time in the regolith. Once implanted, the solar wind can diffuse out of the surface in warm regions, but remain embedded (for long enough times to create OH) in cooler regions. Maps of solar wind residency time as a function of SZA were produced – with increased concentrations in cooler regions, similar to the M<sup>3</sup> results (but with lower concentrations as compared to the IR-derived values). This work is highlighted by an extended abstract for the upcoming 44<sup>th</sup> annual LPSC.

Using a neutral exosphere model developed earlier in DREAM, Sarantos et al [2012] predicted the creation of photo-ion species for comparison to ARTEMIS observations. They also used Elphic et al. [1991] to predict the surface-sputtered ion component. A key result in

comparing the two sources is that the anticipated ion flux from photo-ionization far exceeds that from solar wind sputtering. The results are shown by species in Figure 2. Note that only Ca and Mg has a sputtered ion component that exceed that created the ionization of exospheric neutrals – primarily because these metallic species tend to electrochemically leave the surface preferentially ionized.

**1.2. Plasma.** One of DREAM key findings is that the space plasma environment is strongly coupled to the surface volatile environment – they are effectively indivisible. Proton implantation and sputtering have dramatic effects on surface volatiles – changing the chemistry of the near-surface region.

A good example is the DREAM study of the plasma-volatile connection within polar craters.

While shadowed polar craters are viewed as thermally stable for trapping volatile species like water, the surfaces are energized by solar wind ions that expand into the depressions via ambipolar E-fields. Figure 3 shows an example model from Zimmerman’s kinetic plasma code [Zimmerman et al., 2011, 2012].

The top figure shows the solar wind ions (blue), electrons (red), and sputtered water from the crater floor (green).

As the electrons move into the crater-formed void ahead of the massive ions, a standing electric field (bottom panel) is created adjacent to the crater wall.

This E-field diverts the horizontally-flowing solar wind protons into the crater, where they deposit their energy onto the crater floor. Sputtering yields from an icy surface is near unity for 1 keV protons [Johnson, 1990], thus these solar wind deflected ions liberally release water molecules from the icy regolith on the crater floor.

Some of this water is energetic enough to leave the crater and deposit in adjacent regions. This kind of plasma-volatile simulation is new and shows the evolved thinking DREAM has developed on the solar wind-volatile connection. These results were presented at the DAP-2012 conference June 2012.

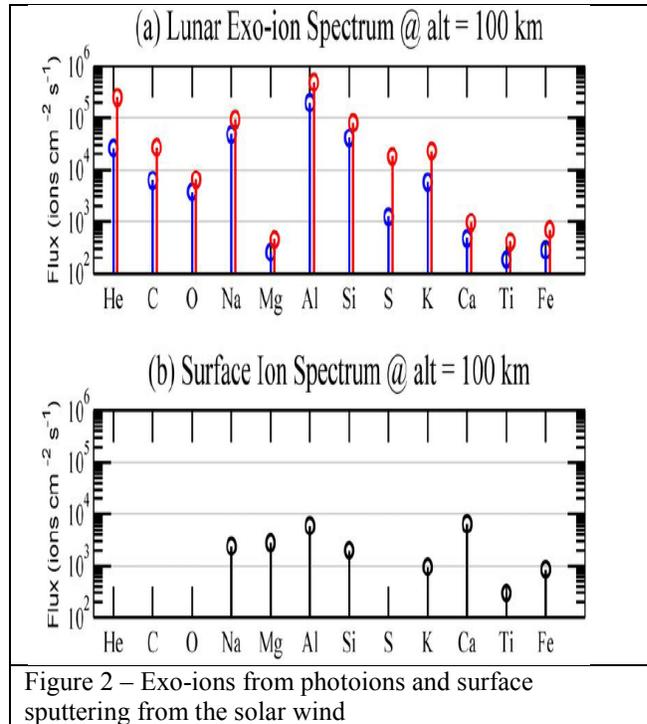


Figure 2 – Exo-ions from photoions and surface sputtering from the solar wind

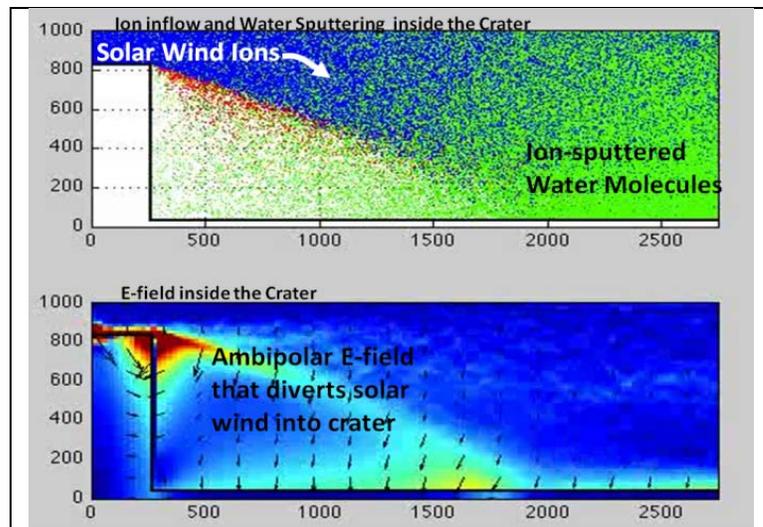


Figure 3 – DREAM’s kinetic simulation of ion expansion into a polar crater & subsequent surface water sputtering from crater floor (from Zimmerman et al., 2012)

The plasma team also examined the pickup ions detected by the ARTEMIS spacecraft. While the ion spectrometers onboard the two spacecraft do not differentiate by mass, the ambient electric and magnetic field conditions act as a natural mass filter that allows an estimate of the ion mass to reach the spacecraft at a given location. The use of the environmental E and B as a ‘poor man’s’ ion mass filter as was previously considered by DREAM’s Hartle.

DREAM team member Andrew Poppe also performed fundamental new studies of the electron and ion entry into magnetic anomalies. In theory, solar wind protons should be capable of propagating down to the surface in the anomaly– the Lorentz  $vB$  force alone is not strong enough to deflect the protons. However, there is a separation of electrons from the ions, since the lower massed electrons are reflected from the anomaly at the topside of the region. An ambipolar E-field develops that slows the ions and reflects a large portion back into the solar wind. This effect was modeled by Poppe et al. [2012].

**1.3.Response to Impacts Modeling Study (RIMS).** In the last ½ of 2012, DREAM team members commenced a focusgf study of the environmental response to impacts at the lunar surface. The objective of RIMS was to understand the evolution of the plasma, volatiles, and particulates from a moderate sized impact in the space environment. The team ran a set of exosphere, plasma, surface charging, and dust plume charging models from similar initial conditions. Co-I A. Colaprete provided particulate size and speed distributions along with estimates of vapor amount and temperature for an LCROSS-like impact plume, and also for a plume from an impact at 10x and 100x LCROSS energies. In Nov 2012, the team held a RIMS team meeting to present results with some interesting new results: 1) The grains in the plume are in a dynamic charging state, starting initially negative (from impact processes like tribo-charging) to positive charged from photoelectron emission over the course of their flight. 2) A plasma pulse is released upon impact that has an unstable front; this due to the electrons repeatedly trying to move ahead of the ions to thus create strong Langmuir turbulence. 3) As this plasma pulse passes over the surface, the surface charge state possibly makes a large transient excursion.4) Based on Monte Carlo modeling, the impact-created neutral gas may develop a bulk flow, and some discussion on the cause of this effect took place at the workshop. The results from this intramural study are being prepared for publication.

**1.4.Applications.** In PY4, the DREAM team was involved in a number of project related activities that are outlined in the Table below.

<b>Project</b>	<b>Associated DREAM Activity</b>
LADEE	DREAM team members as part of the NLSI Dust and Atmosphere Focus Group submitted a letter request to PSD Director Jim Green on the advantage of a LADEE Participating Scientist program. This note was acted upon and resulted in the LADEE GI solicitation.
LRO	The DREAM dust team of Stubbs and Glenar have been working with the LRO LROC, LAMP and star camera leads to look for evidence of dust scattering consistent with the McCoy ‘O’ model.
ESA Lunar Lander	DREAM team members at UCB and GSFC were part of a study group putting together a Phase-A study on a dusty-plasma package. Unfortunately, ESA has shelved the opportunity.
GSFC’s Internal Task Group: Human Exploration Virtual Institute (HEVI)	In FY13, GSFC formed an internal IRAD-funded task group called HEVI to examine the exploration-oriented science capabilities that exist at GSFC. DREAM team members conceived of this group and integrated members of GSFC’s space weather community , radiation specialist, and lunar operations teams. The HEVI team has currently been inventorying these competencies and performing a concept study called ‘Where to hide?’ to identify lunar pits as safe havens for possible further examination as part of an

**2. Inter-team Collaborations.** The table below describes the substantial DREAM connections to other teams in this PY4.

Team	Nature of DREAM Collaboration
CCLDAS (M. Horanyi)	Continue to work on joint modeling and lab studies, including the modeling of a plasma inflow into a shallow crater [Poppe et al., 2012] and a lab study of the wake expansion process (submitted as a LASER). DREAM provided a set of invited talks for the CCLDAS-sponsored DAP2012 workshop held in June 2012.
LUNAR (J. Burns)	DREAM team members supported LUNAR RF antenna studies by providing 50 MHz preamp systems to summer interns examining antenna detection efficiency at deployment. Continue to work on radio systems at the Moon to provide basic knowledge of the RF environment at the lunar surface.
SEPLP (B. Bussey)	DREAM and the SEPLP joint team member Dana Hurley initiated the Friends of Lunar volatiles (FoLV) community focus group that meets monthly to discuss the latest research and exchange ideas. Jason McLain is now a DREAM post-doc who came from SEPLP Co-I's Thom Orlando's group from Ga. Tech.

**3.0 Education and Public Outreach (E/PO).** DREAM's E/PO efforts in PY4 focused heavily on formal education and outreach by providing opportunities for high school students, teachers, and the public to interact directly with DREAM scientists.

**3.1 Formal Education.** The primary components of the E/PO program were a semester-long Lunar Extreme Program (LEP) and subsequent Lunar Extreme Workshop (LEW) held at NASA Ames Research Center (ARC) in November. The goals of the LEP and LEW were to increase student understanding of the Moon as a dynamic place and to increase awareness of the process of science and the types of science, technology, engineering, and mathematics (STEM) careers available to them. A team of ten high school students and one teacher from Valley Christian High School in San Jose, CA, participated (Fig. 4). During the LEP, students reviewed the LEP syllabus and met as a team for discussion and hands-on activities and Webinars with DREAM scientists and collaborators. The Webinars provided the opportunity for students to virtually "meet" science team members before interacting with them in person at the LEW. A local DREAM scientist (Colaprete) also visited Valley Christian High School to meet and talk with them in person about the impact process and his career path. After completing the LEP, student and teacher teams attended the LEW at ARC along with the DREAM team. The students engaged in open discussion with DREAM scientists about their research, learned more about what it is like to be a scientist and the different pathways for doing so, interacted with NLSI leadership, completed a hands-on activity that introduced the Monte Carlo method, observed a cloud chamber to see the effects of cosmic rays in action, and toured several facilities at Ames, including the UV spectrometer lab for the LADEE mission and the lunar dust toxicity lab.

Students reported that the most enjoyable aspect of both the 2012 LEP and LEW was being able to meet and interact with a variety of scientists. Like the students who participated in 2011, the 2012 students unanimously indicated that they now see the Moon as more dynamic than before their participation in the LEP and LEW. Also like the participants of the 2011 LEP and LEW, 67% of the 2012 students said that they are now considering a career in STEM as a result of their participation in the DREAM LEP and LEW.

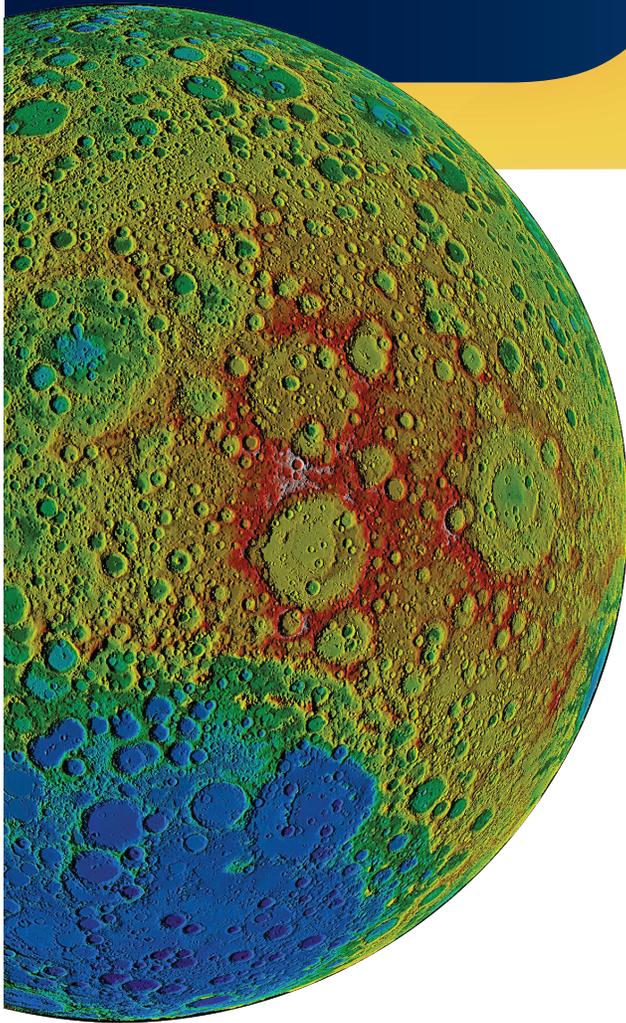


**3.2 Outreach.** The DREAM team was committed to sharing the excitement of its research with students and the general public through a variety of means, including via public talks at schools and other venues and via interacting directly with the public during outreach events such as International Observe the Moon Night (InOMN). During the 2012 InOMN event at GSFC, DREAM was involved in a number of ways, including giving presentations using Science On a Sphere, staffing the “Chat with a Scientist” table, and assisting in planning and implementing the entire event. Over 600 members of the public attended.

# Center for Lunar Origin and Evolution (CLOE)



*Principal Investigator:  
William Bottke (SwRI)*



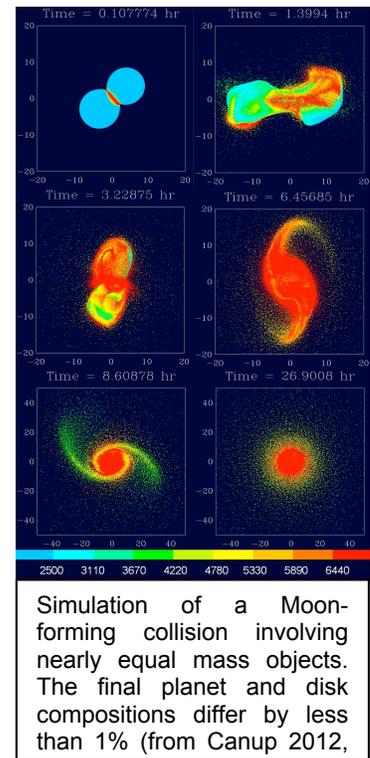
## CLOE Project Report for Year 4 Theme 1: Formation of the Moon.

Hydrodynamical simulations of Moon-forming impacts. In the giant impact theory, the Moon forms from debris ejected into an Earth-orbiting disk by the collision of a large planet with the early Earth. Prior impact simulations predict that much of the disk material originates from the impacting planet. However, the Earth and Moon have identical oxygen isotope compositions. This has been a challenge for the impact theory, because the impactor's composition would have likely differed from that of the Earth. We simulated impacts by much larger impactors than previously considered, and showed these can produce a disk with the same composition as the planet's mantle, consistent with Earth-Moon compositional similarities (Canup 2012). Such impacts require subsequent removal of angular momentum through a resonance with the Sun as recently proposed (Cuk & Stewart 2012; Ward & Canup 2013).

Chemistry of the protolunar disk. We modeled the melt-vapor equilibrium chemistry of the protolunar disk using a modified version of the MAGMA code (Fegley & Cameron 1987). We examined the chemical speciation of the disk atmosphere and the disk's oxygen fugacity for a wide range of bulk silicate compositions (Visscher & Fegley 2013). In general, we find that the disk atmosphere is dominated by SiO, O, and O<sub>2</sub>. We calculate the oxygen fugacity of the saturated silicate vapor, which influences the overall chemical behavior of the disk. Preliminary results show a highly oxidizing vapor corresponding to high H<sub>2</sub>O/H<sub>2</sub> ratios (H<sub>2</sub>O/H<sub>2</sub> ~ 20 at 2000 K), a key constraint for calculating the loss rate of water from the disk.

Accretion of the Moon. We completed a new model that treats the inner protolunar disk as a melt-vapor while the outer disk is modeled with discrete N-body particles (Salmon & Canup 2012). We find that the Moon accretes in ~ 100 years, two orders of magnitude longer than in prior models. Our slower accretion may allow for a partially molten Moon, as favored by geophysical studies and recent GRAIL results (Andrews-Hanna et al. 2012). We are developing a model of the Moon's thermal evolution during its accretion, modeling the Moon in a 3D spherical grid and computing the heat deposited in the Moon from each impact.

Modification of the Earth-Moon system angular momentum by the evection resonance. As the early Moon's orbit expands due to tidal interaction with the Earth it can be captured into the evection resonance with the Sun. Capture excites the Moon's orbital eccentricity and drains angular momentum (AM) from the Earth-Moon system. The amount of AM loss depends on the duration of resonance occupancy. Cuk & Stewart (2012) find substantial AM loss, allowing for a broader range of lunar forming impact scenarios than previously considered viable. We are examining this possibility using the Mignard tidal model that assumes a constant time lag,  $\Delta t$ , of a body's response to tidal distortion. We find that if the Moon is locked into synchronous rotation by a permanent figure torque, it escapes from the resonance too quickly to alter the system AM much. However, if the synchronous spin lock is broken, the resonance state can sometimes persist much longer, with substantial AM loss (Ward & Canup 2013). We are currently examining the escape physics in detail employing both numerical and semi-analytic techniques in order to evaluate the relative probability of these disparate outcomes.



### Theme 2: Observational Constraints on the Bombardment History of the Moon

**Theme 2a. Thermochronometry and the Bombardment History of the Moon.** This year the Theme 2a team (Co-I Mojzsis; Ph.D. students E.A. Frank, M.D. Hopkins; Postdoc N.L. Cates; Undergraduate

*Students* J. Greer; *External Collaborators* T.M. Harrison (UCLA), K.D. McKeegan (UCLA), O. Abramov (USGS), D. Kring (LPI-NLSI)) set several milestones in their collective research progress in studies of lunar rocks, meteorites and the temporal history of thermal events to the parent bodies of these objects. Co-I Mojzsis and his students and postdoc have given at least 20 talks per year from 2009-2012, most of them invited seminars at domestic and international universities or conferences including the International Goldschmidt Geochemistry Conferences (2010, 2011), GSA (2009), AGU (2010), and various other venues. Co-I Mojzsis has also been active in interactions with the media (television, print, radio) with appearances in PBS's NOVA (3x in 4 years) and most recently Into the Wormhole produced and hosted by Morgan Freeman. Each of these appearances touch specifically on topics relevant to NLSI. Doctoral candidates Elizabeth A. Frank and Michelle D. Hopkins both completed their advancement to candidacy examinations in 2012 with anticipated graduation dates in late 2013 or early 2014. Co-I Mojzsis taught the graduate "Cosmochemistry" course to 14 students in Fall semester which has a strong lunar component, as well as the undergraduate course "Search for Life in the Universe", which makes extensive use of NLSI resources in teaching. Over the time span from 2009-2013, S. Mojzsis has taught approximately 7 undergraduate and graduate courses and seminars on topics ranging from the geology of the Moon, to meteorites and the early bombardment environment of the solar system. Recent research results include (i) the first direct evidence for the Late Heavy Bombardment (LHB) on the Earth (Abbott et al., 2012); (ii) documenting the extent of primordial bombardment to the asteroids (Hopkins et al., *submitted*); (iii) searches for evidence of LHB-era bombardment to the oldest terrestrial crust in Canada (Cates et al., *submitted*); (iii) new evidence for the Giant Impact (GI) that formed the Moon from long-lived radiochronometers (Guitreau et al., 2013); (iv) geochemical constraints from platinoid element abundances and W-isotope anomalies for a "Late Veneer" to Earth after the GI but before the LHB (Frank et al., *in prep.*; Willbold et al., *in prep.*). Many of these studies are now coming to fruition.

**Theme 2b: Relative Lunar Crater Chronology.** The goals of this task are to analyze the Moon's impact cratering record to better understand its bombardment history, chiefly from the later portions of the Late Heavy Bombardment (~3.85 Ga) until the present. To address these goals we have computed and analyzed ages of 54 large craters on the Moon with diameters ranging from 50-200 km (Kirchoff et al. 2013; *submitted*). Ages were computed by first compiling small, superposed crater size-frequency distributions (SFDs) observed on the floors of these larger craters, and then fitting these SFDs with the Model Production Function (MPF) chronology. From a histogram of these craters ages, we have discovered that the impactors that produced these larger craters may have a more extended decline from Late Heavy Bombardment (LHB) than has been commonly thought to be true for basins, which ended ~3.8 Ga. Our data show these large craters were forming until ~ 3 Ga. We have also found that many of our computed ages for the crater floors (which may be the original crater floor or reflect later modification) are older than indicated by previous work. We are still exploring the full implications, but one may be that there have been fewer impacts in current epochs (Eratosthenian, 3.2-0.8 Ga, and Copernican, 0.8-0 Ga) than previously thought. There are hints of gaps (or lulls) in the large crater impact flux during this period, which differs from the traditional view that the flux has been roughly constant during late lunar history. Our histogram of ages indicates lulls at 0.9-1.6 Ga and 2.3-3.2 Ga. This shift from having a constant flux to a non-constant flux for large impactors has implications for understanding the impactor population, specifically related to the dynamical evolution of asteroid families and how large impactors dynamically evolve differently from small ones.

### **Theme 3: Determining Lunar Impact Rates.**

Once the Moon's surface solidified, it mainly has been shaped by impacts, making it a witness plate to the late stages of planet formation. Our goal in Theme 3 is to construct theoretical models of the lunar impact history based on new dynamical models of the Solar System.

The first step in this investigation is to develop the most comprehensive model of terrestrial planet formation to date. To this end we have constructed the Lagrangian Integrator for Planetary Accretion and Dynamics (LIPAD) (Levison et al. 2012). In Levison, Duncan & Minton (2012, DPS) we presented preliminary results. We find that 15-40% of the inner Solar System's original mass grinds away before it can be incorporated into a planet. This implies the proto-planetary disk was more massive than previously thought. We also concluded that the final systems we constructed were inconsistent with the observed Solar System in several fundamental ways. This implies our models of planet formation are missing important physical processes. We must identify these processes before we can construct a valid model of the Moon's impact history.

We have also been studying the era of the so-called 'Late-Heavy Bombardment' (LHB) of the Moon. In particular, we have been concentrating on evaluating a model, known as the 'Nice model', that asserts that the LHB was caused by a dynamical instability in the orbits of the giant planets. We have taken a holistic approach - performing new Nice model simulations and evaluating available constraints in order to be able to produce a model that can predict the impact rates on the Moon over time. In Nesvorný & Morbidelli (2012), we reported the results of a statistical study, in which we performed nearly ten thousand numerical simulations of planetary instability starting from hundreds of different initial conditions. We found that the the best results were obtained when the Solar System was assumed to have five giant planets initially and one ice giant, with a mass comparable to that of Uranus and Neptune, which was ejected into interstellar space by Jupiter. The range of possible outcomes is rather broad in this case, indicating that the present Solar System is neither a typical nor expected result for a given initial state, and occurs, in best cases, with only a few percent probability.

On the constraints side, in Marchi et al. (2013a; accepted for Nature Geosci.), we showed that the Ar-Ar impact reset ages of the howardite, eucrite and H-chondrite meteorites between 3.5-4.1 Ga were produced by high velocity impacts (>10 km/s) on their parent bodies. The most likely source of these impactors were high eccentricity asteroids pushed out of the main belt by late giant planet migration (Nice model). They suggest the ~4.1 Ga time marks the start of the late heavy bombardment (LHB). In Marchi et al. (2013b; Nature, submitted), we analyzed the crater and basin record on the oldest Mercury terrains using MESSENGER data. Both indicate the Mercury's oldest surface is ~4.1 Ga, the LHB age determined by Marchi et al. (2013a). In Marchi, Bottke et al. (2013c), we explored Vesta's crater record near/on the young craters Marcia and Rheasilvia. We showed the shape of the impacting size frequency distribution (SFD) has stayed constant for as long as 1-2 Ga. This matches predictions from Bottke et al. (2005) explaining why small impactors hitting the Moon have similar shape SFD over this interval. In Broz et al. (2013), we used numerical models to explore the effects of comets striking the asteroid belt during the LHB, and discussed reasons why the evidence is not more pervasive. In Dones and Levison (2012, DPS), we attempted to constrain the Nice model by determining the mass that hit giant planets satellites during the LHB. We found the Nice model did not violate observed constraints, as has been previously claimed (Nimmo & Korycansky; 2012; Icarus 219, 508). The Earth's orbit places constraints on the Nice model because giant planet instabilities can substantially change its (and the other terrestrial planet's) eccentricity and inclination. In Brassier, Walsh, & Nesvorný (2012, DPS), we showed the terrestrial planets orbits were significantly different after their formation than how they are today. This provides a new planet formation constraint.

Finally, we have started to examine role of asteroid families in determining recent lunar impact rates. Inner main belt families efficiently reach NEO orbits and therefore make up a large share of potential lunar impactors. In Walsh, Bottke et al. (2012), we used measurements of asteroid albedos made by the NASA WISE mission to understand the number, size and age of the dark, carbonaceous chondrite-like asteroid families in the inner main belt. We found a previously known grouping has a different parent asteroid than previously thought, while also discovering an older and more diffuse family never previously identified. These new families, Eulalia and new Polana respectively, are the current dominant sources of primitive km-sized NEOs today.

## 2. CLOE Interactions with Other NLSI Teams

The nature of CLOE's Themes 1-3 have provided us with opportunities for collaboration with several other NLSI teams, particularly those that study early lunar (and solar system) history and those that provide constraints on the Moon's bombardment history.

Science Interactions. Perhaps our chief interaction has been via Simone Marchi, NLSI postdoc, who works for both Dave Kring, CLSE leader, and Bill Bottke, CLOE leader. His efforts have allowed us to team up on numerous papers that have been published (or are on the verge of being published) in science journals such as *Nature* (Marchi et al. 2013), *Nature Geosciences* (March et al. 2013), two *Earth and Planetary Science Letters* (Marchi et al. 2012a,b), and *Planetary and Space Science* (Marchi et al. 2013). These works combine dynamical evolution work of small body populations (e.g., CLOE's expertise; studies of the populations that produced the so-called Late Heavy Bombardment) with sample constraints of bombardment (e.g., CLSE's expertise; impact reset ages of meteorites) and surface expressions of bombardment (e.g., expertise from CLSE and CLOE; cratering records of the Moon, Mercury, and asteroids). Simone's surge of progress was only possible via the NLSI postdoc program as well as the involvement of two teams with very different kinds of expertise.

CLOE director William Bottke has also worked closely with Linda Elkins-Tanton (Carle Pieter's NLSI team) and Rich Walker (Dave Kring's CLSE team). Here we pulled together the expertise of those who do dynamics, lunar and terrestrial geochemistry, and thermal modelers of the early Earth and Moon to understand the signature of the late accretion on inner solar system worlds and ultimately constrain the early bombardment history of the Moon. This has led to a *Science* paper (Bottke et al. 2010), with the constraints for this work used to develop a new lunar chronology (Marchi et al. 2012).

Additional contact with Carle Pieters' NLSI group at Brown University has come via CLOE director Bottke's and deputy director Chapman involvement with the pre-LPSC Microsymposium workshops (see below). This has led to a *Nature* submission led by Simone Marchi, with contributions from Bottke, Chapman, Jim Head and Caleb Fassett on the Marchi et al. (2013; *Nature*) paper discussed above.

Classes: CLOE PI Bottke taught a graduate class on Interdisciplinary Lunar Science at U. Colorado with NLSI PI's Mihaly Horanyi and Jack Burns (<http://lunar.colorado.edu/~jaburns/astr5835/>).

Workshops: NLSI PIs Bottke and Kring jointly organized a workshops entitled Workshop on the Early Solar System Bombardment II (2012; LPI). It was well attended by members of CLOE, CLSE, and Carle Pieters' group at Brown U. (e.g., Jim Head, Caleb Fassett). These workshops have led to numerous joint projects and ideas, many which are on-going. Bottke has also given several invited talks to the two-day Microsymposiums, held every year by Brown U. just prior to LPSC.

Jobs. One of the Co-PIs of CLOE, Amy Barr, accepted a faculty job at Brown U. in 2011.

Collaboration with International Partners. Bottke has visited the University of Western Ontario, home of the Canadian Lunar Institute, has given a seminar there, and has interacted with members of the Canadian NLSI. We are also beginning work on an interesting project closely associated with NEOs. This work will proceed if we are granted membership in SSERVI. Our work on the moon's formation and late lunar accretion has also led to recent interactions with Mahesh Arand's UK Lunar Institute dealing with the delivery of water to the lunar interior via late accretion.

### 3. Education and Public Outreach

In Year 4, the CLOE team continued its efforts to bring lunar science and exploration to a range of audiences through its programs and collaborations with NLSI teams, NLSI Central, and other partners.

*Authentic Lunar Research Projects for High-School Students:* The CLOE team partners with the Summer Science Program, Inc. (SSPI) to involve 72 high-achieving high-school students in authentic lunar science research experiences each year to increase their awareness of lunar research and to encourage them to stay in the science, technology, engineering, and math (STEM) career pipeline. The CLOE project took place over two days in each of the two six-week programs SSP offers at the Institute of Mining and Technology in Socorro, NM (July 22 and 23, 2012) and Westmont College in Santa Barbara, CA (July 29 and 30, 2012). For their lunar research project, the students worked in teams to undertake a computational project investigating the role of chaos in the orbital evolution of the solar system.

*Engaging Children in Lunar Science at Libraries:* A two-day training was conducted in Butte, MT on September 6 and 7, 2012, for 15 librarians and informal educators to build their capacity to communicate about and engage their communities in lunar science. Partnering state library systems recruited children's and youth librarians who primarily work with underserved rural, Hispanic, and American Indian populations in MT and ID. During the trainings, CLOE scientist Dr. Michelle Kirchoff interacted with participants to share CLOE and NLSI science. Attendees undertook hands-on activities from the CLOE Marvel Moon module ([www.lpi.usra.edu/explore/marvelMoon](http://www.lpi.usra.edu/explore/marvelMoon)), networked, became familiar with state resources (e.g., Solar System Ambassadors, astronomy clubs), and planned how to bring the content into their programs. Through these librarians, CLOE research and NLSI science are being brought to rural regions of the country, where the library is often the nearest public center of learning. Two web-based trainings were also offered in August and September to LPI's Explore librarian network and members of the American Library Association and Association for Rural & Small Libraries, disseminating the materials more broadly. Contact and sharing of resources and opportunities is maintained with the CLOE librarians through the Explore online listserv and discussion boards.



Educators undertake an activity in the Marvel Moon module to model accretionary processes that formed the Moon.

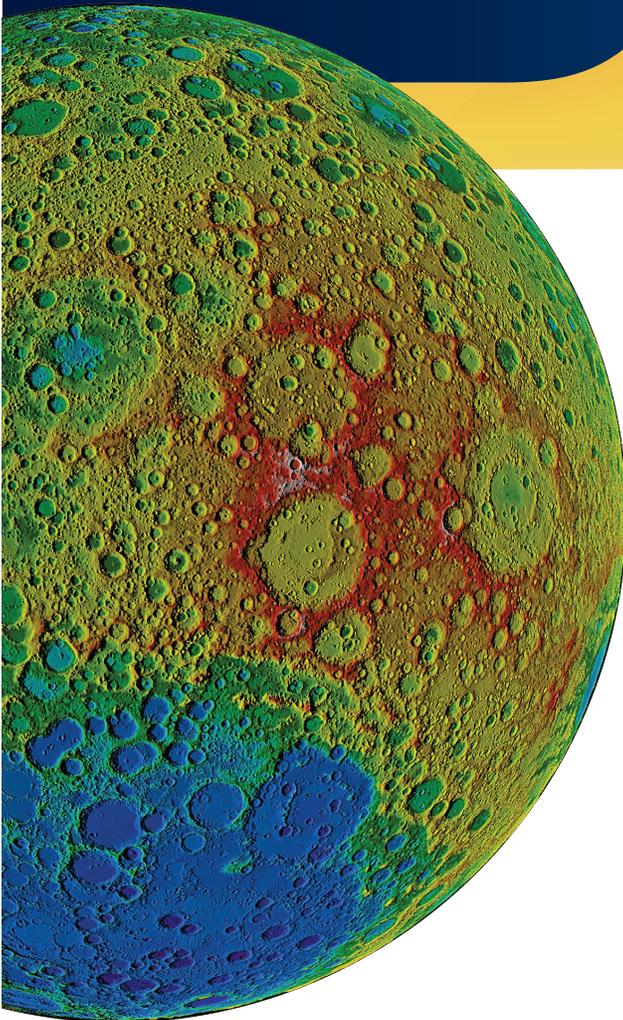
*Engaging the Public through a Student-Designed Website:* The CLOE team collaborated with astronomy classes at the Walden School (Orem, UT) and Lincolnton High School (Lincolnton, NC) to add to the CLOE public web portal to share CLOE and NLSI science, scientists, and activities. Students at these schools interacted with the CLOE team to understand CLOE and NLSI research and present it to the public. Through these interactions, the students learn about lunar content, the process of science, and careers in science. The evolving website (<http://cloe.boulder.swri.edu/>) includes student animations, articles, and art, and opportunities for public involvement.

*Other Efforts:* In addition to these projects, the CLOE team participated in numerous week-long lunar educator workshops with the LRO E/PO team and the APL NLSI team, other formal educator workshops, and the International Observe the Moon Night (September 22, 2012). The CLOE team continued to work with the Moon Mappers citizen science project to help ensure the scientific credibility of the project, as well as shared the project through ongoing programs.

# The Moon as Cornerstone to the Terrestrial Planets



*Principal Investigator:  
Carle Pieters (Brown/MIT)*





# **The Moon as Cornerstone to the Terrestrial Planets: The Formative Years**

Principal Investigator: Carlé M. Pieters  
Brown University  
Institutional Investigator [MIT]: Maria Zuber

## **Fourth Year Report**

February 27, 2013

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<b>5. Students, Young Scientists, New Faculty</b>	<b>5</b>

Our university-based NLSI node is jointly hosted by Brown University and MIT. Our combined team has involved the PI, 19 Co-investigators, and 13 named Collaborators from 8 institutions. 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. We use our combined strengths and experience to address several integrated science themes within a broad implementation plan. *NLSI enables key collaborations.* Four examples of the most recent research are highlighted below, but the full scope of last year's NLSI efforts can be found in the attached publication list.

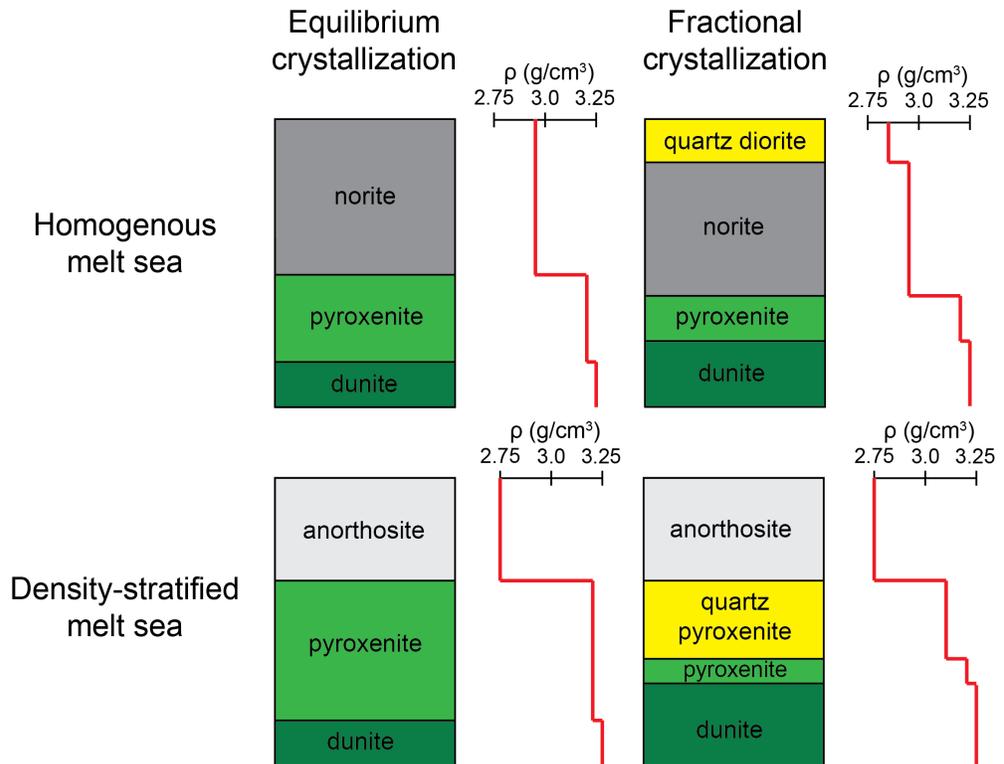
### 1. Science Highlight Examples

*Icarus*, in press 2013  
 Graduate Student Vaughan with Brown/MIT Faculty  
**Geology and petrology of enormous volumes of impact melt on the Moon: A case study of the Orientale basin impact melt sea**  
 W. M. Vaughan, J. W. Head, L. Wilson, and P. C. Hess

The Moon-forming impact generated a magma ocean of  $\sim 10^{10}$  km<sup>3</sup> volume which underwent igneous differentiation to form

the lunar crust and mantle. Basin-forming impacts on the Moon may have generated up to  $10^8$  km<sup>3</sup> of impact melt. Do these mini-magma oceans inside lunar basins similarly undergo igneous differentiation to form new lunar lithologies? To address this we model the petrology of impact melt differentiates in the Orientale basin and other lunar basins, including the South Pole-Aitken basin (SPA). The modeled stratigraphy of impact melt differentiates in Orientale and SPA can be tested with remotely measured compositional constraints.

Model Orientale cumulate stratigraphies and density profiles (to scale) produced by equilibrium and fractional crystallization of homogenous and density-stratified melt seas.



*Proc. Natl. Acad. Sci. USA*, in review 2013

Postdoc Suavet with MIT/Brown faculty and students

**Persistence and origin of the lunar core dynamo**

C. Suavet, B. P. Weiss, W. S. Cassata, D. L. Shuster, J. Gattacceca, L. Chan, I. Garrick-Bethell, J. W. Head, T. L. Grove, and M. D. Fuller

The lifetime of the ancient lunar core dynamo has implications for its power source and the mechanism of field generation. Our new analyses of two mare basalts [10017 and 10049] that are 3.56 billion year old (Ga) demonstrate that they were magnetized in a stable and surprisingly intense magnetic field of at least  $\sim 13 \mu\text{T}$ . These data extend the known lifetime of the lunar dynamo by  $\sim 160$  million years (My) and indicate that the field was likely continuously active until well after the final large basin-forming impact. This excludes both impact-generated plasmas as a magnetic field source and a dynamo from impact-driven changes in rotation rate at this time in lunar history. Rather, our results require a persistent power source like precession of the lunar mantle.



Apollo 17 sample 10017:

2012 *Icarus* in review (3 papers)

PI and several international colleagues

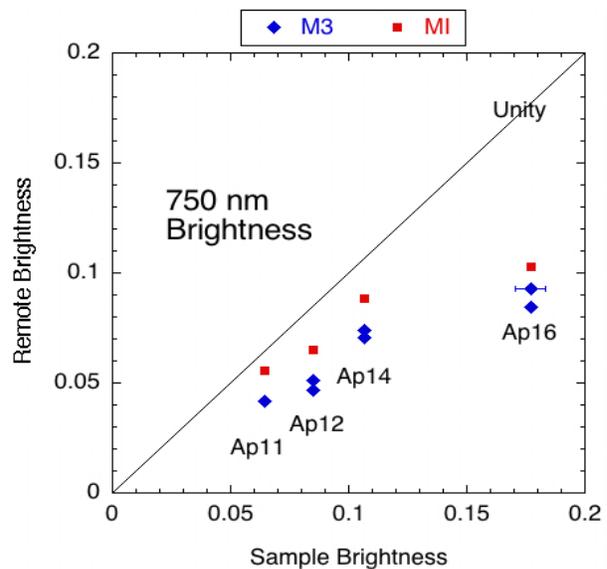
**One Moon, Many Measurements**

Pieters et al., 1: Radiance Values

Besse et al., 2: Photometric Corrections

Ohtake et al., 3: Spectral Reflectance

Lunar brightness values for landing sites measured with independent remote sensors on SELENE and Chandraan-1 are all found to be not as high as that estimated from laboratory measurements of well developed returned soil (“ground truth”). This is now believed to result largely because laboratory measurements of lunar soils cannot retain or duplicate the intricate fine structure of lunar regolith found in the natural space environment.



Comparison of laboratory lunar sample measurements with calibrated M<sup>3</sup> and MI remote data for Apollo sampled sites. Data are for 750 nm and  $i_e = 30,0^\circ$ . In all cases the laboratory measurements of soils are brighter than soils measured in their natural environment on the Moon. Repeat measurements for M<sup>3</sup> are shown where available. Representative error bars for Apollo 16 sample brightness represent repeat measurements.

*Nature Geoscience* October, 2012

Postdoc Liu with U. Tenn. Col Taylor

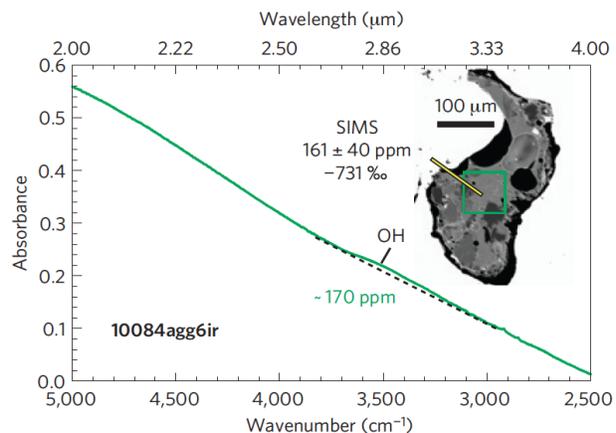
**Direct measurement of hydroxyl in the lunar regolith and the origin of lunar surface water**

Yang Liu<sup>1\*</sup>, Yunbin Guan<sup>2</sup>, Youxue Zhang<sup>3</sup>, George R. Rossman<sup>2</sup>, John M. Eiler<sup>2</sup> and Lawrence A. Taylor<sup>1</sup>

Remote sensing discoveries of hydroxyl and water on the lunar surface have reshaped our view of the distribution of water and related compounds on airless bodies such as the Moon. The origin of this surface water is unclear, but it has been suggested that hydroxyl in the lunar regolith can result from the

implantation of hydrogen ions by the solar wind. Here we present Fourier transform infrared spectroscopy and secondary ion mass spectrometry analyses of Apollo samples that reveal the presence of significant amounts of hydroxyl in glasses formed in the lunar regolith by micrometeorite impacts. Hydrogen isotope compositions of these glasses suggest that some of the observed hydroxyl is derived from solar wind sources. Our findings imply that ice in polar cold traps could contain hydrogen atoms ultimately derived from the solar wind, as predicted by early theoretical models of water stability on the lunar surface. We suggest that a similar mechanism may contribute to hydroxyl on the surfaces of other airless terrestrial bodies where the solar wind directly interacts with the surface, such as Mercury and the asteroid 4-Vesta.

FTIR spectrum and SIMS data of an agglutinate. The coloured square box on the sample corresponds to the spectrum of the same color. The dashed line is the linear fit of the continuum (background) of the spectrum. Concentration estimates using FTIR absorbance are labeled next to the spectrum.



**2. Collaborations**

The NLSI structure has *stimulated and nurtured* exceptionally valuable intra- and cross-team multidisciplinary interactions and has also *enabled* highly productive activities with international colleagues. This spring we will sponsor our fourth “micro-symposia” held just before LPSC in Houston that brings together some of the best minds in the world to seriously discuss ground-breaking topics in lunar science. Brown and MIT have hosted visiting scientists on a regular basis from England, Germany, France, Russia, Ukraine to work with us for periods of time on campus. Once seeded through personal contact, a project is continued typically via remote means (email, skype, google+) and at international scientific meetings. The success of these valuable interactions with scientists around the world are reflected in the attached publication list that involve foreign colleagues such as Basilevsky, Hiesinger, Haruyama, Ivanov, Kaydash, Kumar, Ohtake, Shkuratov, Yamamoto, Wiczorek, Wilson, etc. Our new Asteroid and Lunar Environment Chamber is now undergoing cross-calibrations with a sister facility at DLR. For the last year NLSI kept the RELAB facility open to the broad community for spectroscopic measurements and access to a growing treasure of quality spectra of lunar samples and related materials.

### 3. EPO Report

#### Education Public Outreach Report

The Brown-MIT NLSI Education Public Outreach (EPO) team was very busy training pre-service and in-service educators, working with students and engaging the public in topics of the Moon. A highlight of the year was the publication and release of *Seeing the Moon: An Educator's Guide to using light to investigate the Moon*. The guide is accompanied by interactive white board lessons accessible under *EDUCATION* via the web:

<http://moon.cofc.edu>



#### Educator Professional Development Events

Event / Activity	Date	Location	# Educators	Grades	Underserved
Exploring the Moon: from Galileo to Google Moon related to lunar exhibit	early Spring 2012	Charleston, SC	150	K - 18	Yes
National Federation of the Blind Workshop for Teachers of the Blind	02.27-28.2012	Washington, DC	100	4 - 16	Yes
The Moon for Teachers	08.2012	Greenville, SC	50	5 - 8	Yes
Geology of the Moon - Online course for in-service teachers	Fall 2012	17 states, China*	24	4 - 16	Yes
Igniting Students' Interest in STEM I sponsored by Northrop Grumman Foundation	09.22.2012	Baltimore, MD	100	5 - 8	Yes
Igniting Students' Interest in STEM II sponsored by Northrop Grumman Foundation	10.13.2012	Redondo Beach, CA	100	5 - 8	Yes
Lowcountry STEM Day	11.15.2012	Charleston, SC	200	K - 8	Yes

\*Educator participating from Shanghai, China is an American citizen temporarily teaching in a rural Chinese school. Information and resources shared with her were those limited to public availability.

#### Student-Centered Events



Event / Activity	Date	Location	# Participants	Grades	Underserved
Exploring the Moon: from Galileo to Google Moon exhibit tours and docent training	early Spring 2012	Charleston, SC	4000	K - 18	Yes
Science Pioneers - Girls in STEM	01.20.2012	Kansas City, MO	500	5 - 9	Yes
Kansas City High Schools at the Science Museum of Kansas City	01.21.2012	Kansas City, MO	490	10 - 12	Yes
National Federation of the Blind Annual Conference - hands-on workshop for Teachers, Parents and siblings of the Blind and Visually Impaired	06.29 - 07.03 2012	Dallas, TX	100	4 - 12	Yes
First Day Festival	08.14.2012	Charleston, SC	10000	K - 12	Yes
Sally Ride Science Festival featuring the Moon and GRAIL - I	09.22.2012	Baton Rouge, LA	500	5 - 8	Yes
Sally Ride Science Festival featuring the Moon and GRAIL - II	10.27.2012	Houston, TX	500	5 - 8	Yes
MUSC Children's Hospital	11.20.2012	Charleston, SC	20	5 - 8	Yes