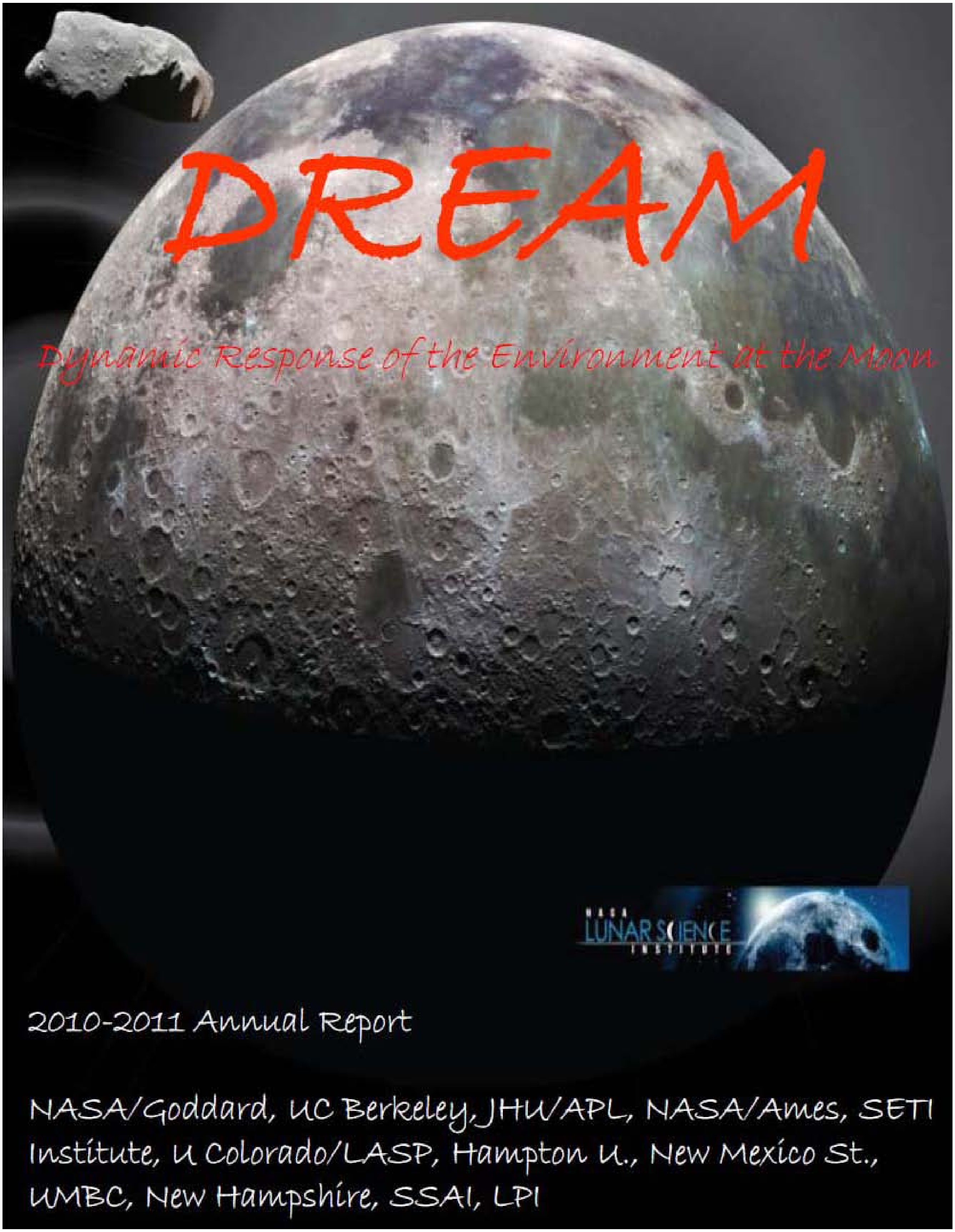

DREAM

Dynamic Response of the Environment at the Moon

NASA LUNAR SCIENCE INSTITUTE

2010-2011 Annual Report

NASA/Goddard, UC Berkeley, JHU/APL, NASA/Ames, SETI Institute, U Colorado/LASP, Hampton U., New Mexico St., UMBC, New Hampshire, SSAI, LPI

DREAM 2010-2011 Annual Report Executive Summary

New results from mission like Chandrayaan-1, LRO, Cassini, EPOXI, and LCROSS all indicate that the lunar surface and near-subsurface harbors unexpected molecules like water, OH, and complex hydrocarbons. This same lunar surface interface is also directly exposed to the surrounding harsh space plasma and radiation environment. The Moon effectively acts as an obstacle to inflowing solar energy and matter and is also being continually bombarded by impacts from meteoroids. As a consequence, we expect some fraction of these H-based surficial molecules to be ejected into regions above the Moon to possibly be detected by exospheric spacecraft like LADEE. It has only been in the last year that the lunar community has discussed the possibly that Moon possesses its own unique water cycle. Just to consider such a possibility suggests that lunar scientists are looking at the Moon from a new environmentally-driven perspective.

The Lunar Science Institute team called " Dynamic Response of the Environment At the Moon (DREAM)" consists of 12 expert partners embarking on an advanced study of the neutral

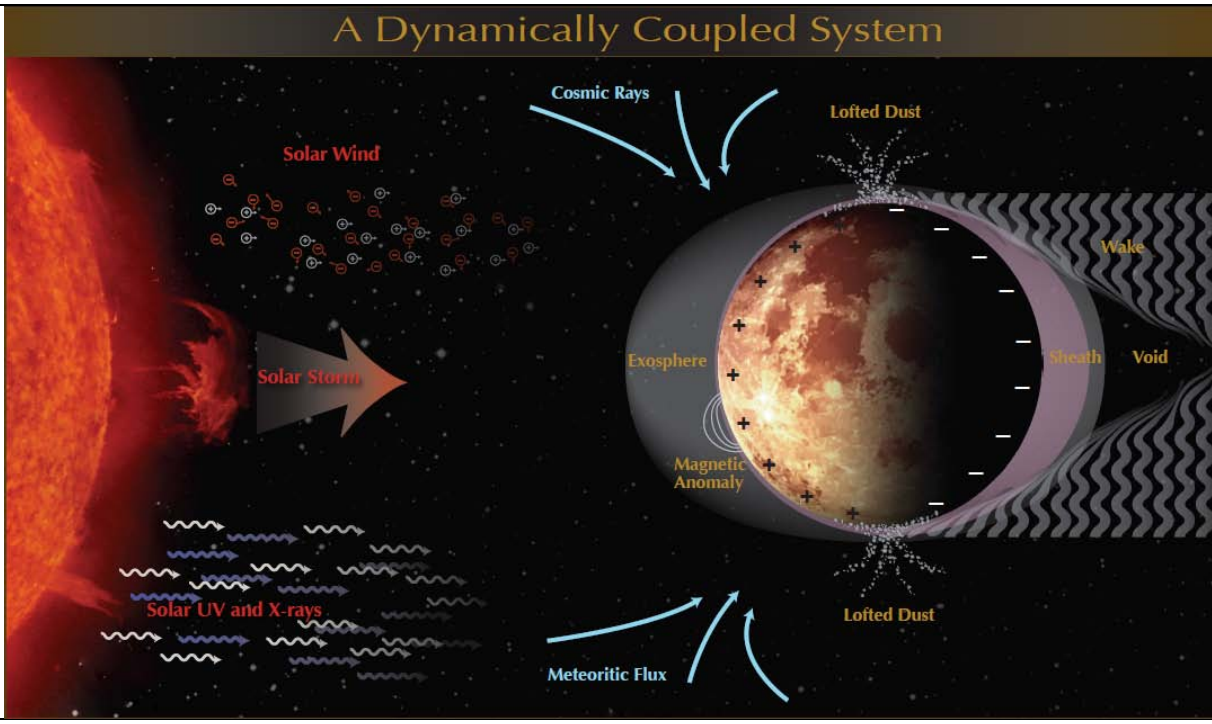

Figure ES.1 caption: The DREAM concept to understand the solar-lunar connection

gas and plasma environmental systems at the Moon. The team especially examines how solar energy and matter affects the lunar surface (including the effect on surficial water, OH, Na, and other sequestered species), and in the understanding of the response of the surface to this solar energy input. DREAM's theory-modeling-data validation study focuses on advancing the knowledge base of the plasma-neutral-surface systems, understanding the Moon's response to the variable solar drivers, finding common linkages between the two systems, and to test these modeled systems via extreme events. DREAM EPO has a primary focus on advancing the teacher and student understanding of lunar extreme environmental conditions, such as the lunar surface reaction to solar storms and impacts/gas releases.

DREAM addresses the fundamental question: **"How does the highly-variable solar energy and matter incident at the surface interface affect the dynamics of lunar volatiles, ionosphere, plasma, and dust?"** To answer this, DREAM has formulated 4 primary science objectives:

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

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

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

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

In the second program year of DREAM, a number of key advancements and discoveries were made in the **understanding of the neutral gas exosphere (Objective 1)**. 1) In support of the LADEE mission, DREAM's Menelaos Sarantos and Rosemary Killen developed a model of impact vaporization and sputtering ejection of surface refractory materials (O, Si, Fe, etc) and demonstrated that these regolith-originating species should be a relatively strong component of the lunar exosphere, reaching high altitudes with significant concentrations. They then found that the LADEE UVS and neutral mass spectrometer would be capable of detecting such species, although the high speed ejections expected from sputtering may make detection problematic for the azimuthally-pointing NMS. 2) DREAM's Richard Hodges developed his LExS exosphere/surface interaction model and found that incoming solar wind protons can charge exchange in the near surface to then be reflected back into space as high energy neutral hydrogen. This picture is different from the conventional wisdom where solar wind protons are believed to be nearly completely absorbed by the regolith, and reemitted in small numbers at thermal levels. This new picture suggests that the surface does not contain a hydrogen enriched layer, and may alter the views and ongoing discussion of water manufacturing at the regolith. 3) In order to explain the M-cubed surficial water finds, DREAM's Dana Hurley has implemented her neutral gas Monte Carlo surface transport code to consider the migration of water from an equatorial source. It was found that such a source could not explain the spatial distribution of water centered about the poles. The very timely results were presented at the 2010 LPSC meeting. 4) DREAM team members William Farrell and Rosemary Killen are also examining the likelihood that the mid-latitude water veneer of 10-1000 ppm is a results of impact vaporization and transport from a water-rich (~5% wt) polar cap regolith.

A number of key advancements were made in the understanding of the **dusty-plasma interaction and ionized gas flow at the Moon (Objective 2).** 1) There was substantial progress of lunar plasma and exi-ion simulations under development at both at UCB and GSFC. UCB hybrids simulations coded by DREAM's Dietmar Krauss-Varben and Pavel Travnicek are now being run with the addition of recent Kaguya-discovered dayside surface-reflected ion beams. The simulations demonstrate that these surface-reflected ions can end up populating the trailing lunar wake, changing the wake dynamics. At GSFC , Particle-in-cell plasma codes are being advanced by DREAM post-doc Mike Zimmerman, who is finding that the plasma expansion process into lunar polar craters is modified by the degree of surface charging. These results are to be presented at the upcoming LPSC 2011 meeting. 2) DREAM's Jasper Halekas and CCLDS's Andrew Poppe teamed up to examine the plasma physics behind the LP observations of negatively charged dayside regions on the Moon. Because of photo-electron emission, the dayside of the Moon should be primarily charged positive. Combining Poppe's PIC simulation with validating LP measurements, it was found that negative potentials may develop due to the formation of non-monotonic potentials and the formation of a layer of accumulating negative charge in regions 10's of meters off the surface. 3) DREAM's Dave Glenar, Tim Stubbs, John Marshall and Denis Richard have reexamined the Apollo 15 and 17 camera images of lunar horizon glow and found that the concentration of dust grains required to obtain the glow brightness levels is a very sensitive function of assumed grain radius. While McCoy's '0' model from the mid 1970's assumes a grain radius of 0.1 microns for the lofted dust, the team found that if this assumed radius is doubled, the concentrations consistent with the observed brightness have to decrease by a factor of 100. Such a study has direct implications for the LADEE dust detection capability: There may be few than expected dust impacts, but each impact may be more intense than originally expected.

DREAM made a set of key advancement in the **integration of neutral, dust, and plasma models** in **application to extreme events (Objective 3).** Specifically, DREAM is planning a June 2011 Lunar Extreme Workshop (LEW) where neutral gas, plasma, and surface charging models will be run in sequence using a common trigger: The May 1998 solar storms. The objective of the LEW is to understand the effect a solar storm has at the Moon, and to determine how long it takes to dissipate storm-generated lunar activity. The results of this workshop will be especially valuable to the LADEE mission scientist, since their observations will occur in 2013, near solar maximum, when solar storm energetic particles and coronal mass ejections are expected to be incident with the Moon. For the DREAM LEWs, the solar storm modulation of sputtered ions, exo-ions, reflected protons and charged dust are to be incorporated into a 2D hybrid plasma simulation and these species will be examined in the code as environmental plasma is modulated in cadence with the May 1998 activity. The storm modulation of sputtered ions and dust have to be calculated separately via a surface interaction sputtering and surface charging models, which will be run preceding the hybrid simulation runs. In year 2, DREAM team members developed a plan for running the set of models in proper sequence, identified key components that need to be developed to make the model integration work smoothly, and are now building the interfaces required for model-to-model connections. Testing of this cross-discipline Solar Storm/Lunar Interaction Merger (SSLIM) Model commenced in Feb 2011.

DREAM team members applied their environmental knowledge in **support of number of missions in 2010-2011 (Objective 4),** including Kaguya, LRO, the LCROSS impacts and the upcoming LADEE mission. Joint DREAM team and LADEE Project Science team members (Greg Delory, Rick Elphic, Tony Colaprete) have used DREAM model results (from Menelaos Sarantos, Dana Hurley, Rosemary Killen, Richard Hodges, Tim Stubbs, Dave Glenar, Jon Marshall, Denis Richard) to further frame the expectations for the LADEE science objectives, especially in the detection of exospheric refractory materials, in observing the lunar horizon glow, and in the search for a water/OH exosphere. The LADEE-DREAM connection involving the very liberal exchange of information is a hallmark accomplishment of this institute. DREAM team members from UCB (Jasper Halekas and Greg Delory) also worked with Prof. Yoshi Saito at JAXA on a set of combined LP/Kaguya lunar plasma studies. DREAM's Halekas spent nearly 2 months in Japan in 2010 working with our collaborators on Kaguya ion mass analyzer and LP/Kaguya wake comparison sets. Some of this work is featured in a review article on the lunar plasma environment to be published as part of the Lunar Dust, Atmosphere and Plasma/Planetary & Space Science special issue. DREAM investigators also provided early science support to the ARTEMIS lunar plasma mission during the initial lunar orbit phases. Already, one paper has been written by DREAM investigators on an early ARTEMIS wake encounter. DREAM helped support this early science activity, especially focusing on ARTEMIS' unique observations of the large-scale lunar wake expansion process which is a shared ARTEMIS-DREAM objective.

DREAM team members were also active in **'Supporting Other Institute Objectives (SOIO)'**. 1) DREAM Participated in a number of E/PO events including Maryland Day 2010 at the University of Maryland Campus and a leading role in the International Observe the Moon Night 2010. 2) DREAM joined with GSFC's Lunar and Planetary Space Academy on lunar projects for undergraduate science and engineering majors in the summer of 2010. One of the interns leveraged this activity to receive a state fellowship to continue their award winning research into the school year. 3) The IT team continued to enhance the DREAM webpage that describes our lunar science (http://ssed.gsfc.nasa.gov/dream/). 4) CoI Lora Bleacher and Collaborator Noah Petro continue to involve DREAM in the Next Generation Lunar Scientist and Engineer (NGLSE). NGLSE's purpose is to engage and develop the next generation of lunar scientists and engineers, and to enable their successful involvement in current planning for the scientific exploration of the Moon. 5) The E/PO team developed a 16-week mini-course for high school students in preparation for the Lunar Extreme Workshops. 6) The E/PO and IT teams developed a DREAM E/PO-devoted website (http://ssed.gsfc.nasa.gov/dream/DREAM/) that is now accessible online. This website will also contain material for the 16-week LEW preparation course. 7) DREAM team members are active participants in NLSI's Dust and Atmosphere Focus Group, which advocates for lunar science that especially emphasizes dusty exosphere and plasma research. 8) Team members continue to be recognized as science leaders by chairing conference sessions at LDAP2010, LSI-Forum, and LPSC. 9) DREAM press releases and web-features in 2010-11 on the electrical lunar polar craters and sodium LCROSS ground-based observations were picked up by the press and distributed widely.

DREAM had substantial **intra-team collaborations** with other NLSI teams, including the formation of a lunar water focus group featuring surface interaction experts from the Ben Bussey's Polar Environment LSI team. These collaborations have been very fruitful, with the surface interaction experts interacting with DREAM team members to understand and develop new ways of looking at electron/surface interactions, adsorption processes, and water/regolith chemistry. Similar ongoing and active interactions are occurring with the other LSI teams, including the CCLSD dust LSI team and the LUNAR astrophysics LSI team.

To summarize, the DREAM lunar science institute provides uninterrupted coherency for its researchers, allows immediate reaction & resource deployment to act on new findings, and fosters the spirit of community-level cooperation that extends well beyond the boundaries of its own institute. These attributes are simply not possible via isolated, nonintegrated SR&T awards. All total in DREAM's first two program years, the team has over 22 science papers submitted to referred journals, provided > 70 talks/presentations at conferences like AGU, Lunar Science Forum, & LPSC, and are mentoring over 18 high school and undergraduates via DREAM's Lunar Extreme Program and GSFC's Lunar Planetary Space Academy. The team has over 30 ongoing lunar-related tasks that interconnect team members, connect across to other NLSI teams, and link to the international lunar community.

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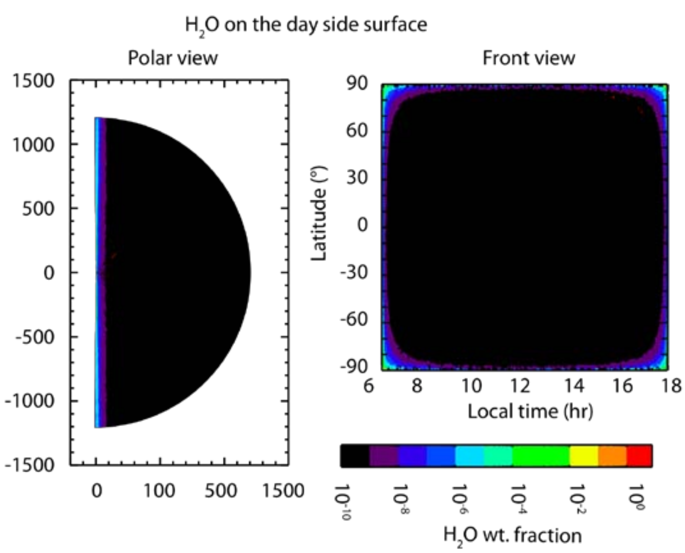
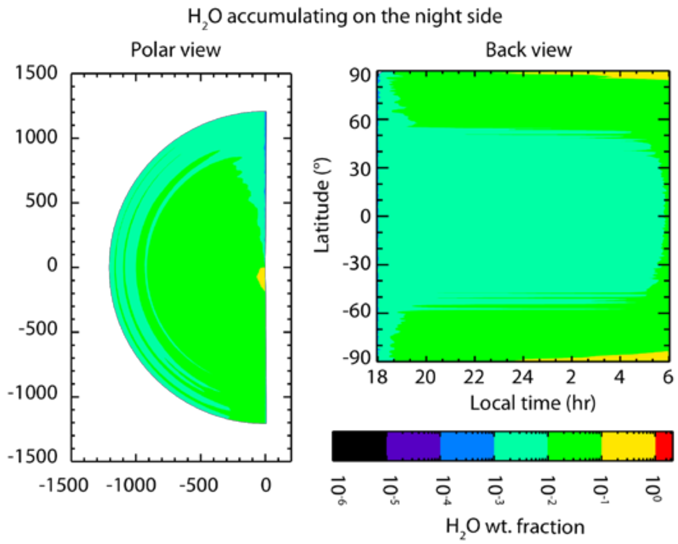
Objective 1: Advancements in the understanding of the Lunar Exosphere

Summary: The lunar exosphere has relationships to the surface: surface composition, surface charging, chemistry and dust; solar inputs including photons, particles and the interplanetary magnetic field; and loss by photoionization resulting in pickup ions that can be related to the neutrals. We have made significant progress in studying the role of the various processes. We have supported NASA missions including LRO and LADEE, both by ground-based observations and by producing models and simulation tools. Our progress toward these various tasks are summarized below.

Progress Reports:

OH and H2O on the Moon (Hurley, Killen). One of the most interesting in finds in 2009 was the discovery of a water veneer at dayside mid-latitudes. DREAM team members have modeled this using Monte Carlo codes (presented at LPSC and Forum). The lunar exosphere model has been applied to the redistribution of OH and H2O on the surface of the moon for comparison with the IR measurements of the Deep Impact/EPOXI mission. We found that a continuous source from solar wind interaction with the regolith would not support the observed surface component if the surface component is H2O. The highest concentrations are near the terminator and on the night side. The nightside surface density of H2O would be a monolayer almost completely filled after one night's accumulation. In contrast however, the solar wind could produce the signal if the surface component is OH.





Figures 1.1. Results of the Monte Carlo surface interaction code for migrating water molecules on the day and nightside.

LExS toolkit development (Hodges). The Lunar Exosphere Simulator (LExS) toolkit is part of the planning effort for the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission. The code is available, on a collaborative basis, for use in other studies of lunar volatile transport. Briefly, LExS can be thought of as a generalized subroutine that can be incorporated into any Monte Carlo program that, in turn, collects statistical data on the behavior of an arbitrary neutral atomic or molecular species in the lunar exosphere. The basic task performed by LExS is to track a free atom or molecule through a sequence of random ballistic trajectories and intervening encounters with the lunar surface. The ballistic part of the code includes the perturbative effects of the gravitational potentials of the earth and sun, resonant scatter of solar photons, charge exchange reactions with solar wind and terrestrial magnetosphere ions, photo-ionization, photo-dissociation, and escape. Simulation of the encounters of atoms or molecules with the lunar surface amounts to random migration in a computer generated, fairy-castle-like structure of loosely packed soil grains that have a realistic size distribution. A recent improvement in LExS is the use of the USGS global lunar digital elevation model ULCN2005 in determining local surface parameters that affect the directional distribution of atoms leaving the surface and where they collide when they return as well as the effects of shadows on temperature. Solar wind impact has been added to the extensive list of options for generating new atoms at the lunar surface. In addition, the surface physics of atom and molecule impacts on soil grain surfaces has been made more rigorous.

LADEE NMS support (Hodges). In principle, the LADEE neutral mass spectrometer should span a sufficiently long time period to detect the episodic venting of argon-40 detected by the Apollo 17 NMS. However, the relevant data will be obtained at various longitudes and altitudes. Relating these data to temporal variations of the total abundance of exospheric argon requires a global model with accurate height variations. LExS based simulations show that the vertical distribution of argon depends strongly on the thermal accommodation of argon at the regolith surface. The Apollo 17 argon data set is not adequate to determine the accommodation parameter. However, it appears that the accommodation coefficient can be measured by LADEE by making argon measurements over the noon meridian immediately before and after certain orbit correction maneuvers. A similar effort is under way to facilitate the determination of the variation of the exospheric helium abundance with solar wind and possibly the venting of radiogenic helium from deep in the lunar interior.

Solar Wind Hydrogen (Hodges). A paper entitled "Resolution of the Lunar Hydrogen Enigma" has been accepted for publication in Geophysical Research Letters. This paper addresses one of the long-standing puzzles of the Apollo era: the failure of the far-ultraviolet spectrometer (UVS) on the Apollo 17 Command Module to detect resonantly scattered Lyman-alpha in the lunar exosphere. A new theory for the interaction of solar wind with the lunar regolith surface is tested by comparing simulated spectra of reflected energetic neutral hydrogen and protons with analogous neutral spectra from Chandrayaan-1 and proton data from the Kaguya mission. Overall, the theory indicates that roughly 1% of solar wind protons incident on the lunar regolith surface exit as energetic protons, and about 98.5% exit as neutral H with super-escape speeds. The remaining 0.5%, which exit as neutral H atoms with sub-escape speeds, form a tenuous exosphere that is compatible with the levels of Lyman-alpha allowed by Apollo 17 observations.

Polar Cap Water Fountain Model (Farrell, Killen, Hurley). DREAM team members are currently formulating and investigating the possibility that the polar icy regolith like that discovered by LCROSS (5%wt of water) may be the source of the mid-latitude water 'veneer' observed in the 3 micron IR bands by Chandrayaan-1, Cassini, and EPOXI. We are considering the possibility that harsh space environmental processes like sputtering and impact vaporization energizes the polar near surface to allow the release and transport of water molecules to mid-latitude regions. Lunar polar regions have long been suspected to sequester water and the recent LCROSS impacts confirm that water can be trapped in the near-subsurface at levels of 5% wt in permanently shadowed regions. Energization processes like ion sputtering and impact vaporization can eject/release these sequestered water molecules with sufficient velocity to allow transport to mid-latitudes. For example, impact vaporization to 4000K releases water molecules at nearly 2 km/sec, to a height of ~800 km and horizontal single-hop distance of 400 km. Such a process occurring in an ice-rich polar regolith could eject water to mid-latitude regions. Preliminary results to be presented at the upcoming LPSC 2011 meeting suggest that if the polar cap region (within 5^{o} of the pole) has a large area of exposed water-rich regolith, then indeed such a source could account for the Chandrayaan-1 and Cassini observations of a mid-latitude water veneer > 10 ppm via ion sputtering, electron & photon stimulated desorption and impact vaporization. However, if the icy-regolith is buried (as suggested by LP neutron spectrometer studies) then far less water is released by the sole process of impact vaporization. The model may connect two water observations that to date have been considered independent. We are now advancing the model prediction for incorporation into LADEE observational campaigns. LADEE should be capable of constraining and validating the model.

Lunar Pickup Ions (Hartle, Sarantos). Pickup ions formed from ionized neutral exospheres in flowing plasmas have phase space distributions that reflect their source's spatial distributions. Phase space distributions of the ions are derived from the Vlasov equation with a delta function source using three-dimensional neutral exospheres. The **EXB** force produced by plasma motion picks up the ions while the effects of wave particle scattering and Coulomb collisions are ignored. Previously, one-dimensional exospheres were treated, resulting in closed form pickup ion distributions that explicitly depend on the ratio r_g/H, where r_g is the ion gyroradius and H is the neutral scale height at the exobase. In general, the current pickup ion distributions, based on three-dimensional neutral exospheres, cannot be written in closed form, but today's computers easily handle them. They continue to reflect their source's spatial distributions in an implicit way. These ion distributions and their moments are applied to several bodies, including He^+ and Na^+ at the Moon, H_2^+ and CH_4^+ at Titan and H^+ at Venus.

Example: Lunar He^+ and Na^+ With B at 45^O From Flow Direction. The typical magnetic field direction at one AU is about 45° from the flow direction [Ness et al., 1971]. Na^+ densities are shown in slide 1, in a plane defined by $\xi = -x_M/r_g = -R_{Moon}/r_g$, which contains the coordinate $\psi = y/r_g$, parallel to the electric field, **E**, and the coordinate $\zeta = z/r_g$, parallel to the magnetic field, **B**. The pickup ion moves perpendicular to **B** in the (ξ,ψ) plane, where ξ is along a component of the solar wind velocity, $V_d = V_b \operatorname{Sin}\theta_b$, with $\theta_b = 45^o$. The density of Na^+ in slide 1when $\theta_d = 45^o$ has a similar shape to that when $\theta_d = 90^o$ while the latter's peak is about 5 times larger. The peak differences occurring when $\theta_b = 45^o$ and $\theta_b = 90^o$ are quite nonlinear and can't be identified with certainty to any specific cause. The usual skewing shows up in that the peak is shifted in the direction of **E** and when **B** is at 45° the peak is also shifted to the left where the ion density is greater.

Figure 1.3 shows the familiar cycloid pattern for Na^+ densities. This time $\theta_b = 45^o$ and $\zeta = -z_M/r_g = -R_{Moon}/r_g$ is the fixed coordinate and the variable ones are $\xi = x/r_g$ and $\psi = y/r_g$. In other words, the observer is in the ion trajectories plane, (ξ,ψ), where the component $V_b \operatorname{Sin}\theta_b$ of the solar wind velocity exists and is perpendicular the magnetic field. Na^+ cycloids are quite clear in both $\theta_b = 90^o$ and $\theta_b = 45^o$ in slide 2. Although a comparison between He^+ and Na^+ densities is nonlinear, it is reasonable to expect Na^+ densities to be sharper than those of He^+ as one transfers from $\theta_b = 90^o$ to $\theta_b = 45^o$ because the scale height of the Na source is smaller than for He. The nonlinear nature is quite apparent.

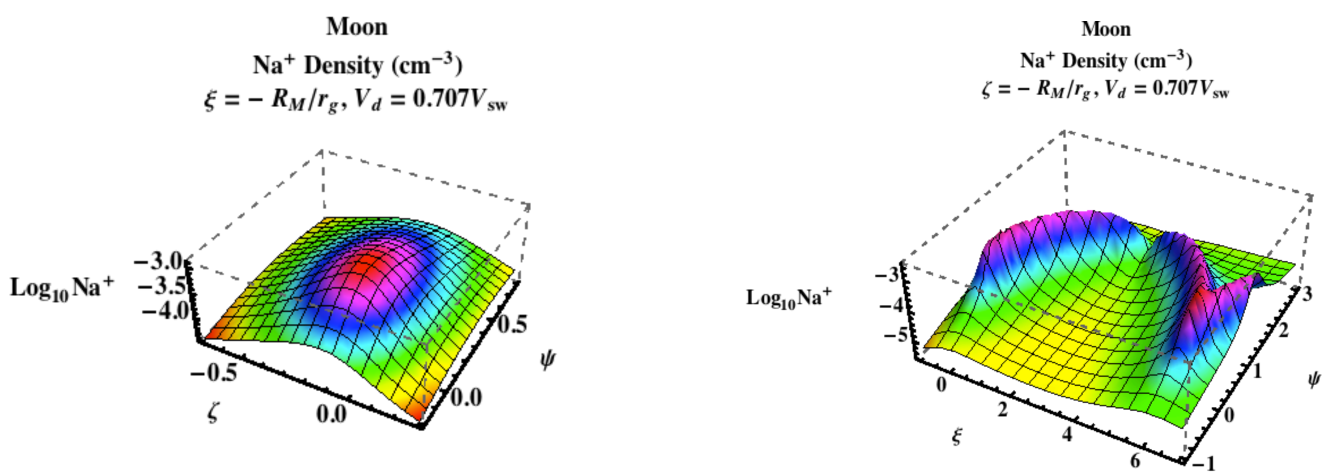


Figure 1.2. The spatial distribution of photo-ionized sodium in gyro-radius scaled coordinates.

Observations and modeling of the LCROSS Plume (Hurley, Killen). We observed emission from sodium(Na) ejected from the Lunar Crater Observing and Sensing Satellite (LCROSS) impact into Cabeus Crater on October 9, 2009, using the McMath-Pierce telescope. A comparison of our observed Na above the limb with simulations that assume a gas temperature of 1000 K indicates that 0.5 - 2.6 (1.5 ± 1) kg of Na were released during the LCROSS impact. Lower temperatures would result in a lower total sodium release. The model of an isotropic expanding cloud best reproduces the observations. Preferential loss of Na in equatorial regions would imply that Na, and other volatiles, should accumulate at higher latitudes over time. Since the lunar Na composition is 0.004 (Heiken et al., 1991), a release of 1.5 kg of Na would correspond to 375 kg of lunar material if the Na were released in proportion to its lunar abundance. That mass is several orders of magnitude lower than the expected mass of material ejected by this impact. This would imply that either the Na was incompletely degassed from the regolith in this event or was instead degassed from a Na/ice mix. This is not surprising, considering the relatively low vapor pressure of silicate rocks at 1000 K (Walter and Carron 1964). A comparison of the Na released as measured here, with the Cl upper limit derived by LAMP are consistent with (but not proof that) roughly equal amounts of Na and Cl in the plume, which would imply a 'salty' water ice at the poles.

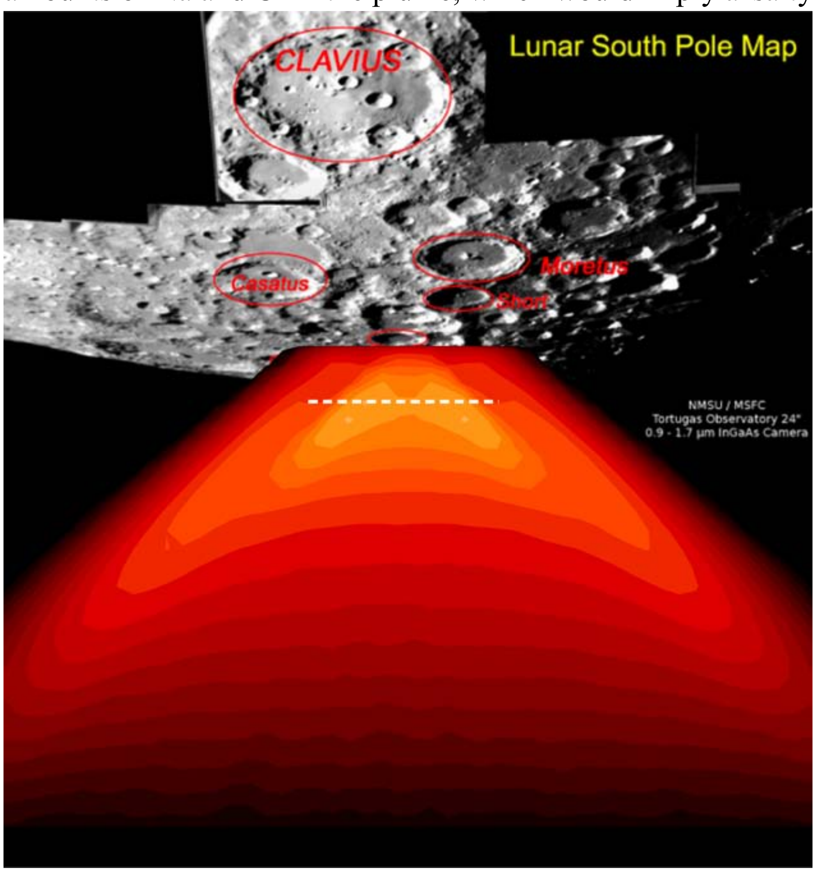


Figure 1.3. A simulation of the impact at the lunar south pole.

An Explanation for Swirl Formation on the Moon (Keller, Stubbs). The bright swirling features on the lunar surface in areas around the Moon but most prominently at Reiner Gamma, have intrigued scientists for many years. After Apollo, and later Lunar Prospector, mapped the Lunar magnetic fields from orbit, it was observed that these features are generally associated with crustal magnetic anomalies. This led researchers to propose a number of explanations for the swirls that invoke these fields. Prominent among these include magnetic shielding in the form of a mini-magnetosphere which impedes space weathering by the solar wind, magnetically controlled dust transport, and cometary or asteroidal impacts that would result in shock magnetization with concomitant formation of the swirls. Another possibility, not previously considered, is that the local magnetic fields can transport and channel secondary ions produced by micrometeorite or solar wind ion impacts. In this scenario, ions, particularly negative oxygen, that are created in these impacts are under the influence of local electric and magnetic fields. Under certain conditions these low energy ions can drift for considerable distances before coming under the influence of the magnetic anomalies where their trajectories are disrupted and focused on nearby areas. These ions may then be responsible for chemical alteration of the surface leading either to a brightening effect or a disruption of space weathering processes. To test this hypothesis we have run ion trajectory simulations that show ions from large regions about the magnetic anomalies can be channeled into much small areas near the anomalies and, although questions remain as to nature of the mechanisms that could lead to brightening of the surface, it appears that the channeling effect is consistent with the existence of the swirls.

Metallic species, oxygen and silicon in the lunar exosphere: upper limits and prospects for LADEE measurements (Sarantos, Killen, Colaprete). The only species that have been confirmed in the lunar exosphere are Na, K, Ar, and He. Models for the production and loss of lunar regolith–derived exospheric species from source processes including micrometeoroid impact vaporization, sputtering, and, for Na and K, photon-stimulated desorption, predict a host of other species should exist in the lunar exosphere. Assuming that loss processes are limited to ballistic escape and recycling to the surface, we have computed column abundances and compared them to published upper limits from the Moon and to detected abundances from Mercury. Only for Ca do the available measurements show clear deficiency compared to the model estimates. This result suggests the importance of loss processes not included in the model, such as the possibility of gas-to-solid phase condensation during micrometeoroid impacts or the formation of stable metallic oxides, and underlines the need for improved spectroscopic measurements of the lunar exosphere. Simulations of the neutral mass (NMS) and visible/ultraviolet spectrometry (UVS) investigations planned by the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft are presented. Our calculations indicate that LADEE measurements promise to make definitive observations or set stringent upper limits for all regolith-driven exospheric species. Our models, along with LADEE observations, will constrain assumed model parameters for the Moon, such as sticking coefficients, source processes and velocity distributions.

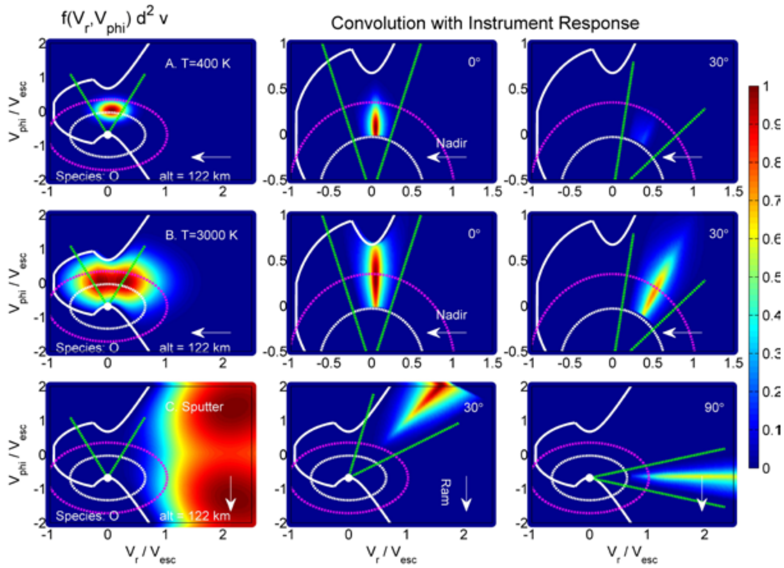


Figure 1.4. (Left column) Velocity distribution of lunar exospheric particles in the equatorial plane. (a) Oxygen accommodated to the local surface temperature; (b) Oxygen from micrometeoroid impact vaporization; (c) Oxygen from sputtering. (Middle and right columns), The relative fraction of neutrals mapping into the open source LADEE NMS (white dot) is shown for ram (0°) and off-ram pointings. Dotted green lines indicate the instrument's effective field of view. Dotted white (magenta) circles centered on the spacecraft indicate the fraction of planetary neutrals not measured when an instrument potential of 0.2 V (0.5 V) is applied to suppress spacecraft outgassing.

Objective #2: Advancements in the Understanding of the Plasma and Dust Environment

Summary: The DREAM Team Objective II group members continued their work this year to understand the lunar dusty plasma environment. We performed studies of lunar dust and plasma, and analogs thereof, utilizing a variety of different theoretical/modeling/laboratory techniques. We studied data from the laboratory and from past and current lunar missions, ranging from Apollo era data collected more than forty years ago, to brand new measurements from the new lunar mission ARTEMIS, to innovative dust measurements in the laboratory. Our simulation capability has also matured greatly, with multiple particle-in-cell and hybrid codes utilized to address specific problems of interest. Furthermore, we have developed a number of new collaborations within the DREAM team, with other NLSI nodes, and with outside investigators both in the US and other countries. A special focus of our investigation this year was developing a better understanding of dust scattering, with the aim of developing predictive capability for future LADEE observations.

Project Reports

A. Simulation Advances and Data/Model Comparisons

Kinetic Simulations of the Solar Wind – Moon Interaction (D. Krauss-Varban & P. Travnicek). One of the more intricate topic areas of our investigations is a better understanding of both the immediate and the long-term effects of the Moon's continuous exposure to the high-velocity streaming solar wind plasma. To that end, we are developing a variety of kinetic simulations to comprehensibly model the Moon's observable impact on the surrounding environment. To ensure being able to develop the best description of all occurring processes, we are starting with two-dimensional (2-D) simulations (see Figure 1.1) to explore the solar wind's parameter regime and to gain fundamental understanding of the processes occurring and their spatial and temporal scales. Subsequently, after gaining experience and confidence in realistically handling the processes and their occurring scales, we will transition to 3-D. One of the topics of interest is the creation of reflected and also sputtered ions in the lunar environment, which both behave vey differently from the mostly moderate-energy ions of the solar wind and – which in the vast majority are protons. As an example, we have started to look into the impact of higher-energy protons of the ever-present energetic tail distributions, and their ability to fill the (otherwise empty) wake region quickly. Another population that competes to gain access to the wake are protons that are reflected from the lunar surface, and then act like "pick-up" ions, with thermal velocities similar to the streaming solar wind (and thus, much hotter than the thermal distribution). Reflected solar wind protons (and other species) act like pick-up ions, in the sense that they find themselves with relative speeds similar to the solar wind (and thus, much higher than their previous solar wind thermal speed). Thus, they have rather large ion gyro radii – comparable to the Moon's diameter. It is apparent that under certain circumstances, such ions play a major role in refilling the otherwise almost empty lunar wake.

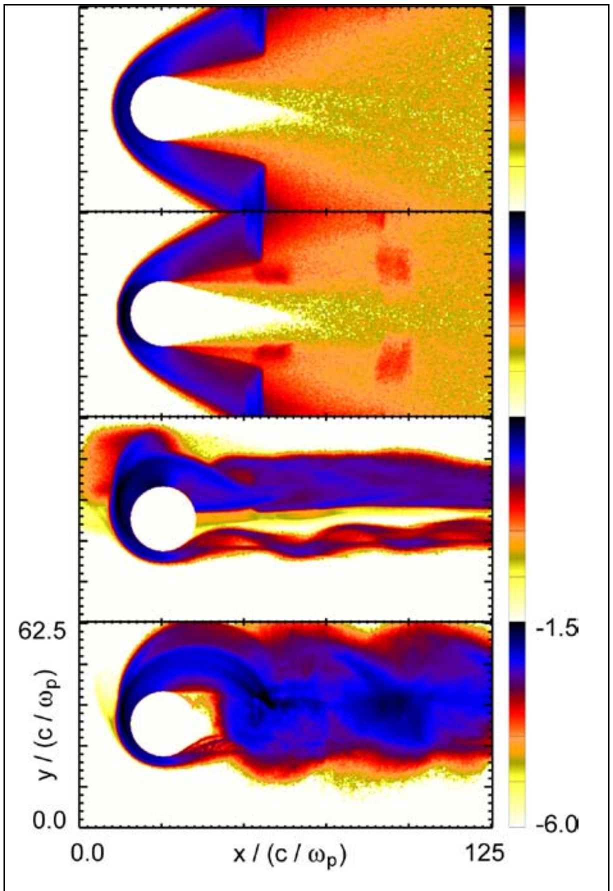


Figure 2.1. Panels show logarithm of the density of reflected solar wind protons, in self-consistent hybrid simulation of lunar wake. The top panel shows specular reflection, while the second panel incorporates a more sophisticated model with angle-dependent reflection efficiency and overlaid diffusely – reflected population. The bottom two panels show two different magnetic field configurations: (panel 3) magnetic field in both the forward (horizontal, *x*) direction and out-of-plane, and (panel 4), magnetic field solely in the out-of-plane (*z*) direction. It is immediately evident that a field component perpendicular to the solar wind direction vastly enhances the density (of reflected ions) in the wake. In addition, an interesting density structure is revealed caused by the ion gyration. (Note that these preliminary simulations are of marginal extent in their vertical directions, leading to a spurious effect at the boundary – but one not important in this discussion).

Investigating the electrical environment in permanently shadowed lunar craters using PIC models (M. Zimmerman, W.M. Farrell, T. J. Stubbs) Anticipating the plasma and electrical environments in permanently shadowed regions (PSRs) of the moon is critical in understanding local processes of space weathering, surface charging and chemistry, secondary ion and electron emission, volatile production and trapping, and charged dust transport. It is also important for future missions to quantify the electrostatic hazards posed to robotic and human explorers during excursions into PSRs under a wide range of solar wind conditions. To investigate crater wake formation and structure we have performed two-dimensional particle-in-cell simulations of the solar wind flowing into a simple topographic depression, including self-consistent surface charging and realistic solar wind conditions (Figure 2.2). Our results support non-charge-neutral theories of plasma wake formation (e.g., Crow et al. 1975, Farrell et al. 2010). As the solar wind sweeps horizontally past the crater depression, hot electrons rush into the void ahead of the more massive ions, creating charge separation just leeward of the crater wall. A downward-pointing ambipolar electric field results, accelerating ions into the crater where they strike the surface at some distance downstream. For simulated craters much deeper than the solar wind Debye shielding length a large negative surface potential develops near the crater wall.

Accumulation of negative surface charge generates an electric field structure that can in some regimes feed back on the infilling wake. Dependencies of the surface potential and charge density profiles on solar wind temperature, flow speed, plasma density, crater depth, and secondary electron yield are being thoroughly explored.

PIC modeling of surface charging in the plasma sheet and comparison to measurements from Lunar Prospector (A. Poppe, J.S. Halekas, M. Horányi) When the Moon encounters the terrestrial plasma sheet, large, unexpected negative dayside potentials (~-500 V) have been measured by Lunar Prospector (LP). We compared these LP measurements with one-dimensional particle-in-cell simulations of the potential above the lunar surface when the Moon is exposed to both solar UV radiation and the terrestrial plasma sheet. The simulations show that large negative potentials can develop due to the presence of stable, non-monotonic potentials. This re-interpretation of previous results has important implications for lunar surface charging and the dusty plasma environment near the dayside surface.

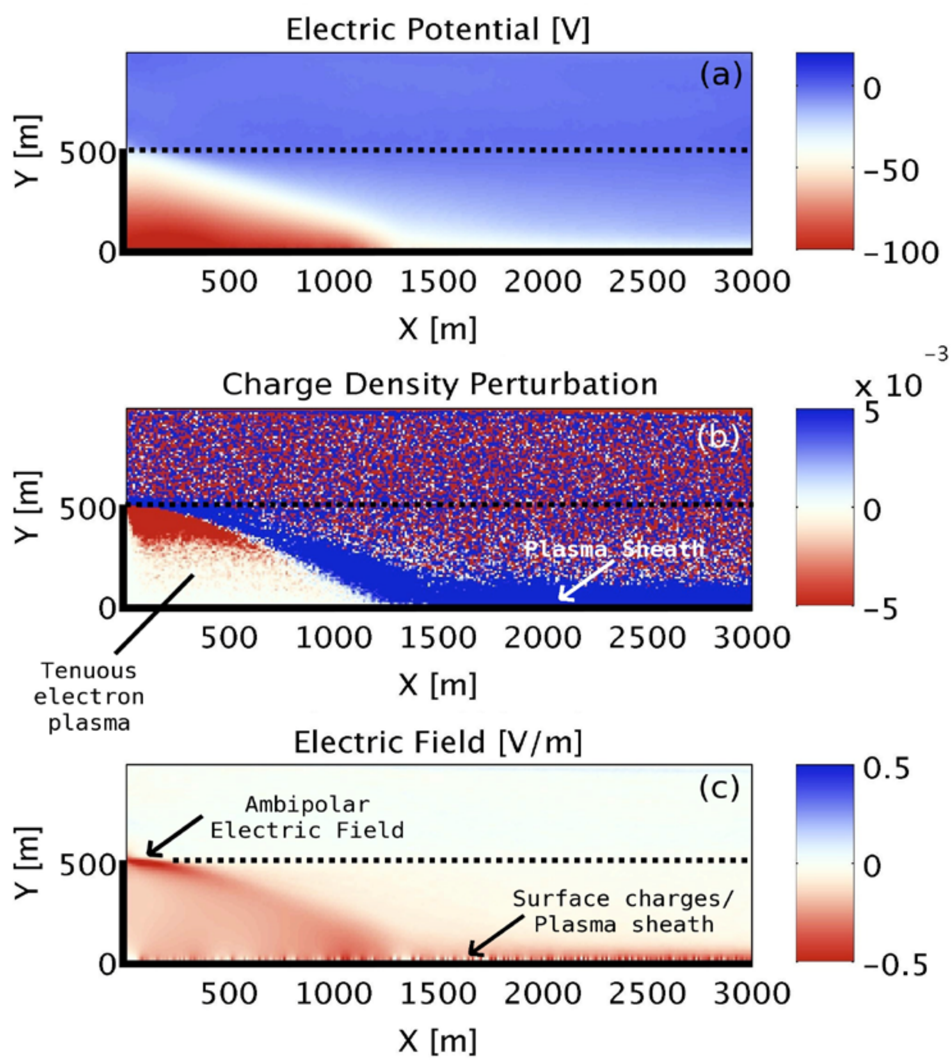


Figure 2.2. Fully 2D simulated plasma wake structure in a polar topographic depression. The lunar surface is denoted by a thick black line, and the initial plasma-vacuum interface is depicted as a dashed black line. Solar wind plasma flows from the left above a height of 500 m, with typical plasma conditions. Thermal electrons initially rush into the wake ahead of the more massive ions (panel b), forming an ambipolar electric field just leeward of the crater wall (panel c) that serves to accelerate ions into the void. Large negative electric potentials occur where only the most energetic electrons can escape the bulk solar wind plasma, and surfaces exposed only to electrons charge highly negative (panel a).

Lunar Surface Charging in the Earth's Magnetotail (T.J. Stubbs) The Moon spends most its orbit immersed in the solar wind, but for ~5 days around full moon it passes through the Earth's distant magnetotail, where it encounters relatively cool and tenuous plasma in the tail lobes, and occasionally the hotter and denser plasma sheet region. The lunar surface is directly exposed to solar UV and the surrounding plasma environment, and so it becomes electrically charged. Surface charging processes can be very sensitive to changing plasma conditions, particularly on the nightside and near the terminator. We have compared and analyzed model predictions in the tail lobes, plasma sheet and solar wind in order to better understand the processes involved. These predictions are based on electron moments from the Lunar Prospector and ISEE-3 missions, as well as the Apollo CPLEE instruments deployed on the lunar surface. Earlier analysis of CPLEE data suggested that the dayside surface electric potential could reach >~200 V positive during traversals of the tail lobes – a factor of ~20 higher than expected. To even achieve surface potentials > ~100 V requires excessively high photo- and secondary electron temperatures, and extreme secondary electron yields that are unphysical. Therefore, the putative CPLEE observations of dayside potentials > ~200 V still appear to defy any theoretically feasible explanation.

Assessing the Role of Dust in the Lunar Ionosphere (T.J. Stubbs) Radio occultation measurements from the Luna 19 mission suggest that electron concentrations above the sunlit lunar surface can be significantly higher than expected from either the photo-ionization of exospheric neutrals or any other well-known process. These measurements were used to infer the electron column concentrations above the lunar limb as a function of tangent height, which surprisingly indicated peak concentrations of $\sim 10^3$ cm^{-3} at ~5 km altitude. It has been suggested that electrically charged exospheric dust could contribute to such electron populations. This possibility has been examined using the exospheric dust abundances inferred from Apollo 15 coronal photographs to estimate the concentration of electrons produced by photo-and secondary emission from dust. The results suggest that electrons emitted from exospheric dust could be responsible for the Luna 19 measurements, and that this process could dominate the formation and evolution of the lunar ionosphere.

Charging and Subsequent Dissipation of a Rover Wheel in a Lunar Crater (T. L. Jackson, W. M. Farrell, T. J. Stubbs) As an astronaut or roving vehicle moves along the lunar surface, electric charge will build up. This charge collected by the roving object will have a dissipative path to either the surface or the ambient plasma, depending upon which path is most conductive. At the lunar terminator region and into night-side regions, the surface is very cold and becomes a very poor conductor, leaving the plasma as the dominant remediating current for dissipation. However, within lunar craters, even plasma currents become substantially reduced which then greatly increases electric dissipation times. In the first year of DREAM, the astronaut charging equivalent circuit model was advanced, incorporating a new tribo-electric source in the circuit in order to mimic the tribo-charging of a roving astronaut or vehicle. The results were presented at the LDAP 2010 conference and a paper titled "Astronaut and Object Charging on the Lunar Surface" was submitted to the Journal of Spacecraft and Rockets. The objective during the second year of DREAM was to determine the nature of charging and discharging for a roving wheeled object in the cold, plasma-starved lunar polar regions. The astronaut charging model was applied as an analog to determine the dissipation times for a rover wheel to bleed off its excess charge into the surrounding plasma, given the environment at various locations within a lunar crater. These results will be presented at the 42nd LPSC 2011 conference.

B. Data Analysis

Re-analysis of solar wind data from Lunar Prospector (J.S. Halekas, G.T. Delory, W.M. Farrell, A. Poppe) We re-analyzed electron distributions measured by Lunar Prospector above the dayside lunar surface in the solar wind. These distributions often have an energy dependent loss cone, inconsistent with adiabatic magnetic reflection, possibly implying the presence of parallel electric fields and/or wave-particle interactions below the spacecraft. Some, but not all, of the observed energy dependence comes from the energy gained during reflection from a moving obstacle; correctly characterizing electron reflection requires the use of the proper reference frame. Our results indicate that the Moon may influence solar wind plasma well upstream from its surface. Magnetic anomaly interactions and/or non-monotonic near surface potentials provide the most likely candidates to produce the observed precursor effects, which may help ensure quasi-neutrality upstream from the Moon.

ARTEMIS first lunar wake flyby analysis (J.S. Halekas, G.T. Delory, W.M. Farrell) We analyzed data from the first ARTEMIS passage through the lunar plasma wake, during which ARTEMIS probe P1 passed ~3.5 lunar radii downstream from the Moon. We observed interpenetrating proton, alpha particle, and electron populations refilling the wake along magnetic field lines from both flanks. The characteristics of these distributions match expectations from self-similar models of plasma expansion into vacuum, with an asymmetric character likely driven by a combination of a tilted interplanetary magnetic field and an anisotropic incident solar wind electron population. We used simple models partly developed under the auspices of DREAM to analyze this flyby. These ARTEMIS observations are ripe for more detailed comparison with the most sophisticated DREAM models, with some of this work already in progress.

ARTEMIS first surface charging measurements (J.S. Halekas, G.T. Delory, W.M. Farrell) We analyzed data from an early lunar encounter by ARTEMIS-P2, earthward from the Moon in the terrestrial magnetotail. Fortuitously, though more than 8,000 km away, magnetic field lines connected the spacecraft to the dayside lunar surface during several time periods in both the lobe and plasma sheet. During these intervals, ARTEMIS made the first accurate and quantitative remote measurements of lunar surface charging, from an observation point almost one hundred times more distant than previous remote measurements of surface potentials. These new ARTEMIS measurements provide solid evidence for negative dayside surface potentials, likely indicative of non-monotonic sheath potentials above the sunlit surface, in the plasma sheet and - for the first time - in the tail lobe. These non-monotonic potentials, much like those analyzed by Poppe and Halekas (described in section A), may prove to be a ubiquitous aspect of the lunar dayside interaction.

Lunar Regolith Entrainment (John Marshall) The Griffith-flaw analog model for lunar regolith behavior has been refined since last year. The model has been integrated with an analysis of electrical stress systems in charged regolith, and it has been determined that all the Griffith parameters can be collapsed into one single parameter that combines the effects of surface energy, elastic modulus, and flaw spacing. When the powder is stressed, therefore, all parameters are expressed through the degree of compaction, which is easily measured. Our focus can therefore be shifted to actually measuring the yield strength of a powder and correlating it to compaction. Various degrees of compaction will be achieved in the laboratory by vibration of lunar regolith simulants in a small tube of a few inches diameter.

C. Special Focus Topic: Path-finding for LADEE

Numerical modeling of scattering by complex dust grains (D.T. Richard, D. Glenar, T. Stubbs, S. Davis) The characterization of exospheric dust populations at the Moon is key to furthering our understanding of fundamental surface processes, as well as a necessary requirement for the planning of future robotic and human exploration. We have developed a model to simulate the scattering of sunlight by complex lunar dust grains (i.e. grains that are non-spherical and can be inhomogeneous in composition) to be used in the interpretation of remote sensing data from current and future lunar missions. We numerically modeled lunar dust grains of various morphologies and compositions and computed their individual scattering signatures using the Discrete Dipole Approximation (DDA). These scattering properties have then been integrated in a radiative transfer code to simulate the light scattering due to a dust size distribution, as would likely be observed in the lunar exosphere at high altitudes (~1-100 km). We have examined three different dust morphologies in a test model: irregular grain, aggregate of spherical monomers, and spherical grains with nano-phase iron inclusions. We have then simulated the scattering by two grain-size distributions (gamma distributions peaking at 0.1μm and 0.3μm grain radius). We have shown that significant differences in scattering properties exist between the analyses employing the widely used Mie theory and our more realistic grain geometries. These differences include large variations in intensity as well as a positive polarization of scattered sunlight caused by non-spherical grains, demonstrating that the interpretation of LHG based on Mie theory could lead to large errors in estimating the distribution and abundances of exospheric dust. This study has important implications for future observations by LADEE.

Laboratory measurements of scattering by dust grains (D.T. Richard, J. Marshall, S. Davis, G. Berlanga (NLSI intern)) The *Ames Lunar Dust Laboratory* is conducting light scattering experiments on various particulate samples in aerosol form and in solvents. One objective of these measurements is the validation of numerical models of light scattering intended to improve the accuracy of interpretation of lunar mission data. The complex polar nephelometer (see below) uses an off-the-shelf version of the LADEE UVS instrument. Additionally, a spectro-polarimeter is currently being developed. The commands of all electromechanical and electro-optical components (including the spectrometer) have been integrated in a single custom controlling software developed in-house. Preliminary data has been acquired for two types of samples (aerosols of talcum powder and micro-silica). Calibration of the setup will be performed with a sample of micro-silica in solvent (see below). Structurally complex particulates will be studied afterward.

Sample Collection for LADEE Nephelometry (John Marshall, D.T. Richard, G. Berlanga) LADEE nephelometry experiments will use both air and water dispersions. For air dispersion there are two issues. First, SEM analysis of the collected dust was inconclusive owing to the fact that the texture of the SEM substrate had features at the same scale as the particles under investigation. Second, flow of air in the dust cloud caused particles to go around the collector. This has been solved by the development of a “capacitor” collector, comprised of two copper plates –one large, one small --connected by a long copper wire. The small plate is immersed in the dust cloud. We charge the larger plate outside the cloud by placing a statically charged plastic sheet next to it. The induced charge in the large plate transfers to the smaller immersed plate, which then attracts dust electrostatically rather than relying on aerodynamic contact. The method has been applied, and will soon be validated by SEM analysis.

LADEE Nephelometry (John Marshall, D.T. Richard, G. Berlanga) An Mk IV version of a dust cloud generator has been developed to calibrate the LADEE UV-VIS instrument. As a possible solution for limitations of previous approaches (see above), liquid suspension of dust has been introduced as a technique – with suspension maintained by agitation with a magnetic stirrer. The instrument does not see the liquid –only the suspended dust. The amount of dust required is a tiny fraction of a gram in a half liter of water –it appears as clear drinkable water when not illuminated, but under halogen lamp illumination, the light scattering signal is very strong. The suspended dust cloud is also perfectly stable through time, and remains at exactly the same dust density. A student (G. Berlanga, funded through the NLSI) has started to do scattering experiments with this setup.

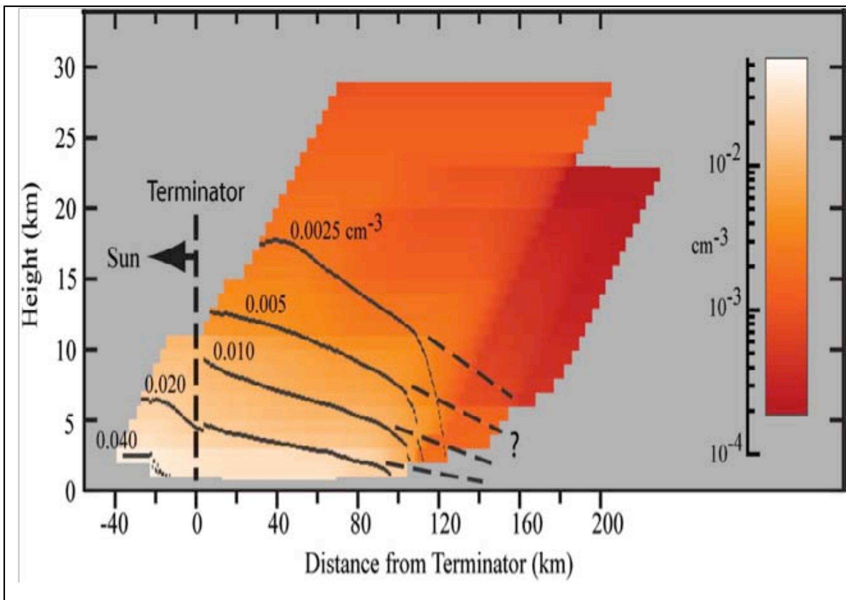


Figure 2.3. Exospheric dust concentration versus height and distance from the terminator near surface sunrise, reconstructed from Apollo 15 orbital limb photographs. Numerical values correspond to grains of 0.10 micron radius, but relative concentration, and thus the shape of the dust exosphere, was found to be insensitive to grain size.

New Predictions of Exospheric Dust Concentration from Apollo 15 Coronal Measurements (D. Glenar)

Excess brightness was observed in Apollo 15 coronal measurements taken near orbital sunset (surface sunrise), and attributed by McCoy to forward scattering of sunlight by lunar exospheric dust grains. The McCoy study constituted a cursory examination of the data set and provided coarse estimates of dust concentration near the terminator. We reanalyzed these measurements in more detail using the known sightline geometries combined with a Mie scattering code and a stabilized linear inversion algorithm. We found dust concentrations (for 0.1 μm radius grains) of ~0.01 cm^{-3} at 10 km altitude with dust column mass of 3-6 x 10^{-10} g cm^{-2}. We also produced a two-dimensional map of dust concentration versus altitude and distance from the terminator. The dust exosphere is found to extend into shadow a distance somewhere between 100 and 200 km, depending on the uncertain contribution of coronal-zodiacal-light to the total brightness. Similar examinations of Apollo 15 and 17 photographs near orbital sunrise (surface sunset) revealed no such obvious excess light contribution. This suggests the possibility of a dawn-dusk asymmetry in exospheric dust related to sporadic meteoroid impacts, or else episodic changes due to coincident meteoroid streams. This picture of the dust distribution above the lunar terminator at one epoch should place new constraints on exospheric dust transport models, and help define observations planned for the Lunar Atmosphere and Dust Environment Explorer (LADEE).

D. DREAM Plasma and Dust Extensions

Review of lunar plasma science (J.S. Halekas, G.T. Delory, W.M. Farrell) Jasper Halekas and co-authors wrote the first new review article on lunar plasma science since the Apollo era. This paper, containing a mix of review material and new analysis results supported by NLSI funds, should provide a valuable resource for current and future lunar scientists, including those analyzing ARTEMIS, LADEE, Chandrayaan, Chang'E, and Kaguya results.

International collaboration with Kaguya MAP-PACE team (J.S. Halekas, G.T. Delory) Jasper Halekas traveled to Japan and worked with the Kaguya MAP-Pace team at ISAS in Japan for two weeks this summer. This interaction has already led to collaboration on modeling of ion reflection from the surface, and promises many productive future international collaborative opportunities, since the Kaguya team is quite eager to leverage DREAM team modeling experience to interpret their data.

ARTEMIS mission support (J.S. Halekas) Jasper Halekas has provided extensive support to the ARTEMIS mission, thereby building bridges between NLSI and current mission planning and operations. Halekas has already written two papers on ARTEMIS data, both utilizing modeling partially developed and/or refined through NLSI (described in more detail in section B). Halekas participates in mission planning for ARTEMIS, has given a number of talks publicizing the mission and the first results, and spoke at the most recent senior review as an advocate of the potential of ARTEMIS for mission science.

Masten Flights (John Marshall, Greg Delory) Greg Delory and John Marshall have secured a series of microgravity flights from Masten Space Systems based in the Mojave desert. This collaboration was brokered through Ames and HQ. We have developed flight hardware that has USML heritage and hope to fly it this year. The experiments relate to fundamental physical processes affecting dust dispersion and aggregation, and it is our intention to feed results into the DREAM mix.

Russian LUNA GLOB (T. Stubbs) Tim Stubbs with support of other DREAM team members is in collaboration with Igor Mitrofanov and other leaders of the LUNA Glob program on scoping the detection of lunar surface lofted dust via the LUNA GLOB dust detector. Ideal view angles and detector sensitivity were compared with current knowledge and theory on dust transport provided by DREAM. A presentation was given at a meeting in Moscow in January 2011. The collaboration is very fruitful.

Objective 3: System Integration and Extrema

Summary: In understanding extreme events, DREAM can investigate and test the coupling that exists between neutral gas, plasma, dust and the surface. In the last program year we saw substantial development in an integrated neutral-plasma-dust model to be implemented in the upcoming Lunar Extreme Workshop (LEW) in June of 2011. The team worked on cross-model interfaces and adding unique elements to the hybrid plasma simulation code making it the most advanced to consider the lunar plasma and exo-ion environment. The team also did substantial work on modeling the LCROSS impact gas and dust plume - an impact being another form of an extreme event.

Progress Report

Lunar Extreme Workshop Solar Storm Lunar Interaction Model: In early 2011, the DREAM team will attempt to merge models that have not been previously connected. We will consider the effect of a solar storm (the May 1998 storm) on the lunar surface, exosphere, and plasma environments. To do this, many of DREAMs exospheric, plasma, surface charging, and polar environment models will be run from a common data set and sequenced such that the output of one model will be used as the input of another model.

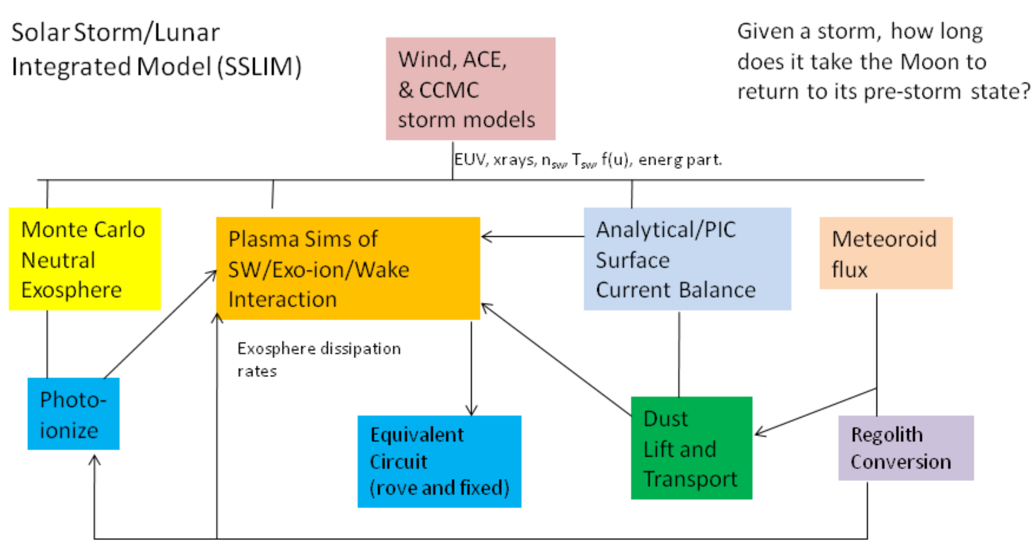


Figure 3.1- The system layout for the SSLIM integration effort. Each box represents key data or models while arrows show the interaction between models.

Figure 3.1 shows the flow of the Solar Storm Lunar Interaction Model (SSLIM) model. WIND and ACE data of the May 1998 solar storm applicable to the SSLIM have already been collected and passed to the team. Currently, models are being updated: UCBs Hybrid plasma code is being updated to include lunar charged dust, reflected solar wind ions, exospheric photo-ions, and sputtered ions. Such a code for lunar applications has never been developed before. The inclusion of the known environmental ions will make the model as close to the lunar environment as possible. The new inclusion of dust has only been applied to one other hybrid simulation of a planetary body: The recent modeling by N. Omidi for Enceladus.

A key element being develop for the code is the surface ejection of sputter ions in response to protons and heavy multi-charged ions in the solar wind. Specifically, the latter species has a much higher yield. Preliminary results by R. Killen and M. Sarantos suggest that the sputtered ions yields vary as $(M Z^2)^n$ where n is 1 to 2, and as such, the larger mass multi-charged ions incident at the surface will have substantially greater ability to sputter ions off of the surface as compared to the nominal solar wind proton. Such heavy ions have larger relative concentrations typically within the driver gas of a coronal mass ejection (CME). We will model the effect of such heavy ions on the surface to determine the variation of sputtered surface refractory species (like Si) with the passing of a solar storm/CME. Such SSLIM results will have direct applications to the LADEE mission which will be sampling the sputtered gases from the lunar surface during solar maximum, when CMEs are expected. Such effects have not been incorporated into a hybrid simulation for the lunar plasma system.

LCROSS Impact Sodium Modeling: Impacts represent another form of extreme events at the lunar surface. In Oct 2009, the LCROSS Centaur booster stage impacted the Moon at close to 2 km/sec within a permanently shadowed polar crater. The impact released a large volume of volatile species including water, sodium, CO, and other complex molecules. DREAM's Rosemary Killen and Dana Hurley continue their modeling effort in understanding the evolution of the sodium gas cloud that left the surface at a temperature of ~1000K. Two publications have resulted from their modeling studies. Their work suggests that about 5 kg of sodium was ejected from the ~5000 kg plume. The work is discussed further in Section 1 of this report. Two papers have resulted from these studies.

LCROSS Impact Ejecta Dust Plume Charging Model: Besides modeling the gas plume, DREAM team members Farrell and Stubbs are leading an effort to model the particulate ejecta charging. Lab studies indicate that impact ejecta typically charge negative, but these grains propagate into a plasma that acts to discharge/alter the grain's original charge state. In the case of LCROSS, at about 800-m above the floor of Cabeus, the ejecta propagates into sunlight and should undergo intense photo-electron emission that acts to reduce the negative charge on the grain and eventually will create a polarity reversal on the grain charge state. This effect has been modeled by the DREAM dusty-plasma team. A surprising result is that, once in sunlight, the grains take nearly 100 seconds to change polarity. However, the grains emit strong electric currents as they propagate into sunlight. Figure 3.2 shows the model results that will be presented at the upcoming LPSC 2011.

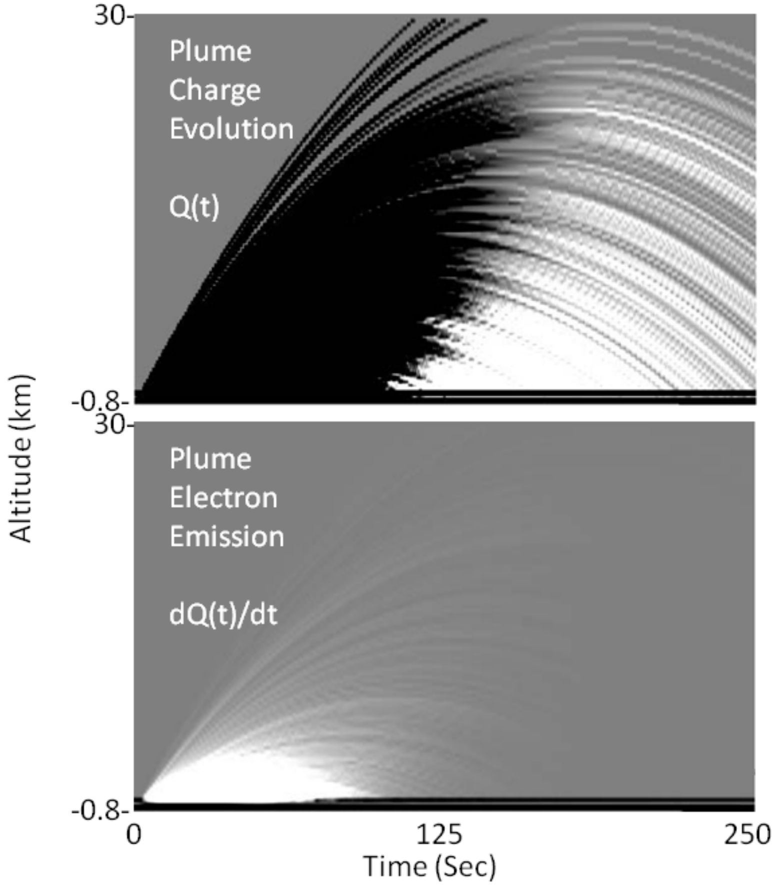


Figure 3.2- The evolution of charge (Q) and charge emissivity (dQ/dt) of a vertical particulate plume consisting of 5000 test grains ranging from 0.4 to ~6 microns in size. In the top panel, regions of negative polarity are black, and positive polarity are white (Black is < -0.1 fC; White is > 0.1 fC). In the bottom panel, the white regions indicate that the plume particulates are emitting electrons and hence charging increasingly positive (Black is < -.02 fA; White is > 0.2 fA). It takes close to 100 seconds for the grains to emit enough photoelectron current to reverse polarity from their initially negatively tribo-charged state.

Regolith Conversion of Solar Wind Protons the Neutral Hydrogen: Applying his LExUS model developed under DREAM, Co-I Dick Hodges recently submitted a manuscript to GRL suggesting that a large portion of the inflowing solar wind is re-injected back into the space environment as neutral hydrogen. As such, the traditional view that Moon 'absorbs' the solar wind is re-examined in this work. Hodges also cited recent Kaguya observations of 1-10% reflection of protons back into the space environment and incorporates IBEX observations of neutral hydrogen to help validate his measurements. This modeling clearly presents a very new connection between the plasma and neutral environments, with the surface acting as transforming medium to convert energetic plasma into a new source of neutrals. The topic is discussed further in Section 1.

Surface Reactive Chemistry and DREAM/Georgia Tech Collaborations: Chemical sputtering from the lunar surface (and Mercury) is believed to create an energetic exosphere, with gas temperatures that far exceed those expected from species thermally accommodated to the surface. While DREAM has expertise in the exospheric modeling, the team found a great resource of surface interaction chemistry with the team at Georgia Tech, Thom Orlando and Greg Grieves, who are both part of Ben Bussey's Polar Environment LSI team. Thom has made a visit to GSFC and gave a presentation featuring electron stimulated desorption processes, explaining new Auger mechanisms that release neutrals via the triggering from solar wind electrons. While there is much study on the release of neutrals by ions, elecrtron release processes are a point of new mutual study. Our interactions with the Polar Environment LSI team are detailed further in Section 6.

Objective 4: Mission Applications of DREAM Environmental Studies

Summary: DREAM team members continue to have deep involvement in recent and planned lunar missions, and have actively participated in community advocacy. This participation has supported the interpretation of existing lunar misson data and has helped future missions fine tune their science goals and objectives. In addition, some DREAM team members have direct roles in these missions in addition to their membership in the NLSI – enabling a seamless interface to the resources available within the DREAM group.

A. Lunar Mission Support

DREAM has collaborating mission footprints in LRO via DREAM team members Rich Vondrak, John Keller, Dana Hurley and Tim Stubbs, in LADEE via DREAM's Rick Elphic, Greg Delory, Anthony Colaprete, and Richard Hodges, ARTEMIS via DREAM's Jasper Halekas, Greg Delory, and William Farrell, in Kaguya via collaborative ties with Prof. Yoshi Saito at JAXA, Jasper Halekas, and Rick Elphic, and in LCROSS via DREAM's Anthony Colaprete. These connections are critical in maintaining DREAM's relevance to NASA's spacecraft projects. Advances in mission support include the following:

Lunar Prospector: Under DREAM, Co Jasper Halekas continues to lead a group on the analysis of LP electron and magnetometer data. A key paper on the lunar plasma environment lead by Halekas featured a new surface potential map based on LP electron spectrometer measurements. Halekas and CCLDS's Andrew Poppe also discovered that the frontside surface of the Moon may have a downward directed E-field that accelerates photo-electrons into the larger space environment. This may be a discover of a precursor electrostatic layer ahead of the Moon, indicating the presence of an upstream obstacle in the solar wind flow. Both of these papers have been submitted in PY2 of DREAM.

LRO: DREAM team members J. Keller, R. Vondrak, D. Hurley and T. Stubbs all actively participate in LRO activities. As an LRO Participating Scientists, T. Stubbs used his shadowing and solar wind inflow code to examine in detail the sunlight and ion flow around Ryder crater, the same crater examined in detail for the 3 micron absorption/water signature in Peiters et al. (2009). This work was presented at LPSC 2010. D. Hurley continues to support the LCROSS plume and exosphere studies performed by LAMP, and was a key (second) co-author on a LAMP/LCROSS paper published in Science on the LAMP UV observations of the LCROSS gas plume.

LCROSS: DREAM team members Rosemary Killen and Dana Hurley continue their modeling of the LCROSS sodium plume, with one paper published and another in press on the modeling efforts. Also, DREAM dusty-plasma investigators W. Farrell and T. Stubbs have developed an LCROSS analog particulate discharging model that features the electrical interaction of the plume ejecta material with the photo-electron rich environment during its trajectory. This ejecta plume modeling will be presented in the upcoming LPSC 2011 meeting.

LADEE. Three DREAM team members – R. Elphic, G. Delory, and A. Colaprete – are part of the Lunar Atmosphere and Dust Environment Explorer (LADEE) team. Elphic and Delory are the Project and Deputy Project Scientists, respectively, while Colaprete is the PI for the UVS instrument. All three have been able to draw upon DREAM resources to support science planning activities – utilizing models of the exosphere by R. Killen and colleagues, as well as dust models from T. Stubbs and D. Glenar. Additional laboratory work by J. Marshall has aided the LADEE UVS team by providing constraints on dust scattering observations likely to be obtained during the course of the LADEE mission. A set of papers predicting the dust environment (including the re-analysis of the Apollo camera images) and predicting refractory atom concentrations in the exosphere where submitted in PY 2 of DREAM.

Kaguya. DREAM's J. Halekas has continued an ongoing international collaboration with the plasma (PACE) team from the Japanese Kaguya mission. J. Halekas worked at the PACE team home institution (ISAS, near Tokyo) for two weeks this past summer, utilizing his extensive experience in Lunar Prospector data to assist them with the interpretation of similar data obtained on Kaguya. This collaboration has already proven fruitful in the past, with the DREAM team at SSL providing models to explain solar wind proton reflection recorded by the Kaguya plasma package. The PACE team is increasingly willing to share data and insight on the lunar plasma environment, and thus it is anticipated that DREAM team members will continue to provide crucial modeling and interpretation of Kaguya results. Co-I Elphic is also a member of the PACE science team for the ion mass spectrometer component, in addition to being involved in the DIVINER instrument on LRO.

ARTEMIS. DREAM's Halekas, Delory and Farrell are Co-Investigators on the ARTEMIS lunar mission, utilizing two spacecraft from the THEMIS constellation to study the lunar plasma environment. Both team members have contributed to science planning for upcoming lunar encounters, which will culminate with Lunar Orbit Insertion (LOI) sometime during the summer of 2011. Co-I Halekas has fulfilled a key role in the data analysis of existing ARTEMIS lunar encounters, involving the dynamics of the lunar plasma wake and measurements of lunar surface charging, with several papers submitted and/or in press.

ETDP-Dust. DREAM team members Farrell and Stubbs have been involved in aiding exploration efforts by defining the lunar dust plasma environment as part of ETDP-dust. Unfortunately, 2010 was the closeout year for that project with final report presented to the ETDP leaders at Langley. We continued to interact and support the ETDP-dust team (Mark

Hyatt at GRC, who is also a DREAM collaborator) in evaluating technical and operational solutions to the problem of lunar dust for human explorers, and in considering possible applications for NEOs and small bodies, which may also be future exploration targets. Wanda Peters and Sharon Straka at GSFC are both ETDP-dust project leaders and DREAM collaborators, in place to ensure (in part) a connection between the ETDP dust mitigation strategy and the environment that the proposed technologies will operate within.

B. Supporting New Mission Concepts

Nanosat Mission Concept: DREAM co-is Halekas, Delory, and Co-I R. Lin have been working with the NASA Ames Research Center in the development of instrument concepts and science goals for a Nano-satellite mission to the Moon to study lunar magnetic anomalies, led by Ian Garrick-Bethell at the University of California, Santa Cruz.

ESA Lunar Lander: A joint DREAM/CCLDS team supported a Czech proposal for a formulation study for a build of a dusty plasma package on a proposed ESA lunar lander. In this case, the European group recognized the two LSI teams as US leaders in this field, and as a combined team created an international group on the development of this package. The opportunity is a great example of NLSI's extension well beyond the borders of the US.

Masten Suborbital Flights. Greg Delory and John Marshall have secured a series of microgravity flights from Masten Space Systems based in the Mojave desert. This collaboration was brokered through Ames and HQ. We have developed flight hardware that has USML heritage and hope to fly it this year. The experiments relate to fundamental physical processes affecting dust dispersion and aggregation, and it is our intention to feed results into the DREAM mix.

Russian LUNA GLOB. Tim Stubbs with support of other DREAM team members is in collaboration with Igor Mitrofanov and other leaders of the LUNA Glob program on scoping the detection of lunar surface lofted dust via the LUNA GLOB dust detector. Ideal view angles and detector sensitivity were compared with current knowledge and theory on dust transport provided by DREAM. A presentation was given at a meeting in Moscow in January 2011. The collaboration is very fruitful.

C. Community Advocacy and Support

LSI D&A Focus Group. Under the auspices of the NLSI, DREAM PI Farrell and CCLDS PI Horanyi formed a community-wide lunar dust and atmosphere focus group (D&A FG). This group met for the second time at the Lunar Dust Atmosphere and Plasma workshop on Boulder in January 2010 and a third time at the 2010 LSI Forum in July. At these meetings the group considered the Lunar Explorer program line as a way to get easy access to the Moon (see update on this concept below under "Lunar Mission Opportunities). The focus group also agreed that NLSI should broaden its charter to consider NEO and small bodies, given the exospheric processes occurring on these bodies has similarities to those of the Moon. The highlight for the group was the actual LDAP meeting where we not only met to discuss process and programmatic issues but also shared goals for outstanding new science. The CCLDS team did an exemplary job organizing the effort. A dedicated special issue in PSS will include papers from the meeting.

Lunar Mission Opportunities via a new Lunar Explorer Program. Last year the DREAM team began to explore the notion of developing a "Lunar Explorer" program, designed to provide rapid, low-cost, high science-return missions to the Moon to enable a continuation of exciting lunar science over the next decade. The concept was presented at the Jan 2010 Lunar Dust Atmosphere and Plasma (LDAP) workshop held in Boulder (sponsored by M. Horanyi and CCLDS team) and later in July at the Lunar Science Forum to the Dust and Atmosphere Focus Group. The concept was picked up by NLSI-central with Greg Schmidt suggesting a white paper be written on the LE concept, which would then be vetted to HQ by NLSI-Central. A draft of the white paper was completed.

Subsequently, ESMD released plans to fly the Exploration Scouts as part of the Exploration Precursor Robotic Program (xPRP) line, some of which could go to the Moon, thus effectively fulfilling the desire of DREAM and NLSI members for a low-cost lunar science and exploration program. The PI-class, rapid build xScouts missions were very similar in structure to the LE line. Unfortunately, at the moment it is far from clear whether xScouts will be implemented in the current programmatic and budgetary environment. As a result, the DREAM team plans to continue to advocate for the development of a low-cost lunar exploration program – modeled on successful, ground breaking missions such as LP and LCROSS, as well as LADEE, currently under development – as a necessary component in order to maintain a program of active lunar science for the foreseeable future.

The draft of Lunar Explorer white paper is included in the Appendix.

#5 Supporting Other Institute Objectives (SOIO)

Summary: Beside DREAM's primary objectives described in section 1-4, DREAM investigators also participated in a large number of actives to promote lunar science to other scientists and to the larger community. These activities are described herein.

Project Report

- DREAM Participated in a number of E/PO events including Maryland Day 2010 at the University of Maryland Campus and played a leading role in the International Observe the Moon Night 2010. In the latter, the DREAM and LRO E/PO teams worked very successfully in tandem to incorporate as many observing sites as possible, including creating an InOMN observing site for our troops in Afghanistan.

- Team members made over a half-dozen public presentations to large groups about DREAM-related lunar science.

- In 2010, DREAM co-investigators joined with GSFC's Lunar and Planetary Space Academy on mentoring a set of undergraduate science students over 7 weeks in the summer. The student projects included water surface chemistry, a study of mercury in polar craters, and writing software to read ALSEP/SIDE suprathermal ion data. One of the interns, Mindy Krzykowski, leveraged the summer research activity (SIDE data processing) to receive an Alaska Space Grant Scholarship to continue the research in the school year. See http://ssed.gsfc.nasa.gov/dream/summerintern.html for more information on the work Ms. Krzykowski is doing with DREAM scientists.

- The IT team continued to enhance the DREAM webpage that describes our lunar science (http://ssed.gsfc.nasa.gov/dream/). A DREAM dedicated E/PO page is now online and will host a study guide for students participating in the Lunar Extreme Workshops. The primary DREAM web page is also currently undergoing construction to include redesign incorporating a dynamic DREAM logo.

-DREAM CoI Lora Bleacher and Collaborator Noah Petro continue to involve DREAM in the Next Generation Lunar Scientist and Engineer (NGLSE). NGLSE's purpose is to engage and develop the next generation of lunar scientists and engineers, and to enable their successful involvement in current planning for the scientific exploration of the Moon.

- The E/PO team developed a 16-week mini-course for high school students in preparation for the Lunar Extreme Workshops. Students from Baltimore's Seton-Keough and Greenbelt's Eleanor Roosevelt High Schools will participate in the course, this concluding with their participation in the Lunar Extreme Workshop in June 2011.

-DREAM team members are active participants in NLSI's Dust and Atmosphere Focus Group, which advocates for lunar science that especially emphasizes dusty exosphere and plasma research. A group meeting was held in July 2010 concurrent with the Lunar Science Forum, and the group communicates periodically via email and the ResearchGate web site. The group continues to advocate for the LADEE mission which continues to be threatened by cost overruns in other SMD programs.

-Team members continue to be recognized as science leaders by chairing conference sessions at LDAP2010, LSI-Forum, and LPSC.

- DREAM welcomed new post-doc Mike Zimmerman who is stationed at GSFC. Mike did his graduate work at the University of West Virginia specializing in plasma and fluid simulations. In his short time at GSFC, Mike has already built a 2D particle-in-cell code of the plasma expansion into polar craters with the results to be presented at the upcoming LPSC 2011. Currently, a number of post-doc candidates are interacting with DREAM team members at GSFC and UCB for possible post gradation positions.

- A set of press releases and webfeatures included DREAM scientists, including a press release and videocast of lunar polar craters, podcast of the extreme lunar environment and DREAM activities, and a web feature on the ground based detection of sodium during the LCROSS impacts. USAToday also wrote a story on Killen et al.'s sodium find suggesting that the lunar water is 'salty'. A web feature was released on 2/17/1 on the sodium detection ("Waiter, there are metals in my lunar water") that has been picked up by a number of news organizations.

-DREAM (Jasper Halekas) and CCLDS (Mihaly Horányi) team members participated in a lunar media workshop lead by the Colorado consortia of LSI teams. Also participating were several other active lunar scientists (including Bill Bottke, another NLSI node lead), a former astronaut (Jeff Ashby), a former associate administrator of NASA (Alan Stern), and numerous members of the professional print and broadcast media. This outreach effort showcased NLSI science from many nodes, including DREAM, to the top members of the science media. A set of DREAM team members at GSFC also took local media training during PY2.

#6 DREAM interconnection to other NLSI Teams

Summary: DREAM lunar science activities extend well beyond the boundary of its own virtual institute. In fact, DREAM has formed strong partnerships with other LSI teams and these interactions have provided key science support to further aid the DREAM objectives.

Examples of DREAM interactions with other LSI institute teams

Joint DREAM/SEPLP water subgroup. After the M^3 and LCROSS water discoveries, a group of exospheric and surface interaction experts from DREAM and SEPLP institute (Scientific and Exploration Potential of the Lunar Poles**,** PI Ben Bussey) meet regularly to discuss possible scenarios for lunar water creation via the solar wind and other solar wind/surface interaction subjects. The DREAM group has expertise in modeling the atom/molecule migration and the plasma environment, while the SEPLP subgroup led by Karl Hibbitts has expertise in surface interactions/quantum solid state physics. The teams nicely complement each other. For example, the SEPLP group has knowledge of Auger electron interactions with the surface that are capable of releasing bound molecules via electron stimulated desorption. This input is entirely new to the DREAM group and can be added as a source to exospheric models. There is also a laboratory component to each group, and they interact to obtain the best procedures to simulate lunar plasma conditions. The DREAM plasma team recently sent information to the SEPLP lab team on solar wind conditions at the Moon for simulating in the lab. We have group telecons about every 6 weeks, and we are looking into the possibility of taking on a post-doc from the SEPLP team at Georgia Tech.

DREAM/CCLDS connections. We currently have a number of active joint investigations with CCLDS (Colorado Center for Lunar Dust and Atmospheric Studies) team. Andrew Poppe (CCLDS) and Jasper Halekas (DREAM) have one submitted manuscript and one in preparation on surface charging, the sheath, and electron emission. They have found that Poppe's simulations of non-monotonic sheath potentials can explain some unusual properties of electron propagation from the surface as seen in the Lunar Prospector data being examined by Halekas, especially anomalous negatively charged regions on the lunar dayside. With our mutual interest in crater surface charging, CCLDS is performing a set of lab experiments to simulate plasma flow at craters for comparison to recent models of Farrell et al (DREAM) and Poppe (CCLDS). DREAM team members strongly encouraged & supported the recent CCLDS-sponsored LDAP Jan 2010 meeting which cemented a strong bond between groups. Jasper Halekas has participated in several successful collaborations with CCLDAS, fostering cross-pollination between different NLSI nodes.

DREAM and CCLDS teams also wrote a joint white paper on a **Lunar Explorer (LE) mission line,** PI-class, low cost, rapid response missions to the Moon (the white paper is included in the appendix). The concept was presented at CCLDS's LDAP workshop in Jan 2010 and later at the LSI-forum (Dust and atmosphere focus group meeting) in July of 2010. The LE concept was replaced by the xScout program and thus there was not further development of the white paper. The white paper is included herein in the Appendix.

DREAM/LUNAR interactions. The LUNAR team wants to place sensitive electronic RF instrument on the lunar surface, and have interacted with DREAM team members on the plasma environmental influence on landed systems. We have had a set of meeting at GSFC on this topic. For example, the LUNAR team is examining the feasibility of placing a thin-sheet antenna directly on the lunar surface. A concern discussed at a joint DREAM-LUNAR meeting is that electrostatic sheer stresses may actually make the sheet move/perturb its position. We recently examined this possibility and presented the result as a poster at the Lunar Science Forum. Based in part on discussions with DREAM group members, the use of RF techniques to understand the plasma environment has also been integrated into proposed LUNAR astrophysical packages. We have a model of success with joint team members in each group, like Stuart Bale, Justin Kasper, and Bob MacDowall who work both DREAM and LUNAR sides, applying knowledge of the lunar plasma environment to LUNAR RF system applications.

Tactical Intra-team Collaborations

-DREAM team members collaborate at the tactical level with Carle Peiter's "The Moon as Cornerstone to the Terrestrial Planets: The Formative Years" . Noah Petro at GSFC gave a talk at the August DREAM team meeting on the latest findings in the Chandrayaan-1 M-cubed, and we informally discuss ideas on water synthesis at the Moon with PI Peiters as often as possible.

-ESA Lunar Lander: A joint DREAM/CCLDS team supported a Czech proposal for a formulation study for a build of a dusty plasma package on a proposed ESA lunar lander. In this case, the European group recognized the two LSI teams as US leaders in this field, and as a combined team created an international group on the development of this package. The opportunity is another great example of NLSI's extension to the international level.

#7 DREAM Education and Public Outreach Annual Report, 2011

A. Formal Education:

Lunar Extreme Program

DREAM's education and public outreach (E/PO) program is focused on student and teacher participation with scientists. The primary component of the DREAM E/PO program is two Lunar Extreme Workshops (LEWs) and the supporting materials developed for each LEW. The LEWs, which will be held in 2011 and 2012, will bring together scientists and modelers from the DREAM team with advanced high school students and their teachers. The LEWs will allow student and teacher participants to interact directly with scientists and to experience the process of science in action. Participation in LEWs and pre-LEW training will expose students to science, technology, engineering, and math (STEM) careers and engage them in learning new STEM content.

In program year one, we focused on developing the pre-LEW curriculum or syllabus. The DREAM E/PO team worked with a local physics teacher, Ms. Yau-Jong Twu, from Eleanor Roosevelt High School to develop the curriculum and to map the resources and activities to the National Science Education Standards and the American Association for the Advancement of Science Benchmarks for Science Literacy. In addition, Ms. Twu assisted the E/PO team in developing a plan and schedule for recruiting student and teacher participants and implementing their pre-LEW training.

In program year two, we refined and finalized the first half of the syllabus. We also worked with an external evaluator to develop our evaluation plan and tools, such as student and teacher surveys. In addition, we also worked with a Web designer to design and build the DREAM E/PO Website (http://ssed.gsfc.nasa.gov/dream/DREAM/). We advertised our pre-LEW training program, called the Lunar Extreme Program, to high school educators in the MD/DC/VA area in fall 2010, which resulted in the selection of two student/teacher teams, one located at Eleanor Roosevelt High School in Greenbelt, MD and another at Seton-Keough High School in Baltimore, MD. The Lunar Extreme Program was launched in January 2011 and will be ongoing through June 2011, at which point the students will travel to Goddard Space Flight Center to participate in a LEW with DREAM team members. Students read and review the resources in the syllabus on their own at home. Their progress and understanding is checked during discussions with their larger student/teacher team during regular meetings once a week. These regular meetings take place after school. During the meetings, students receive instruction and participate in hands-on activities. They also participate in Webinars with DREAM E/PO and science team members. The Webinars provide the opportunity for students to virtually "meet" science team members before interacting with them in person at the LEW. The Webinars also give DREAM team members an opportunity to provide context for the curricular topics within the DREAM framework while also introducing students to STEM careers.

B. Outreach:

Classroom and Public Talks

The DREAM team is 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. Participation in such events allows the team to reach a large number of people and to provide them with a perspective of the Moon and lunar science with which they may not be familiar. Although the number of participants at such events may be small, these types of events allow for more intimate interaction and discussion between the scientist/speaker and the audience. Several DREAM team members have given public lectures about the Moon and DREAM's science goals at a variety of venues. Speakers and venues are listed below:

- January 2010 – Bill Farrell spoke with 3 students from the Lunar and Planetary Science Academy at NASA Goddard Space Flight Center.
- March 2010- Noah Petro and Lora Bleacher organized the Next Generation Lunar Scientists and Engineers meeting at LPSC for 60 people, including several DREAM members.
- May 2010 – Jasper Halekas gave a talk on the lunar space plasma environment and the Moon as a plasma laboratory to 12 journalists in Boulder, CO in collaboration with other NLSI teams.
- May 2010 – Telana Jackson spoke to 20 second grade students about electrostatic charging and the Moon at Stevens Forest Elementary School in Columbia, MD.
- May 2010- Telana Jackson met 2 undergraduate students from Morgan State

University. She spoke with them about her career path.

- June 2010 – Rosemary Killen gave a talk to 20 undergraduates at University of MD, College Park.
- July 2010 – Bill Farrell gave a presentation on DREAM to 25 teachers, grades 6-12, at the Lunar Institute for Teachers, organized by Andrea Jones and Brooke Hsu, at NASA Goddard Space Flight Center.
- September 2010 – Greg Delory gave a talk about water on the Moon to community college students and 5 high school students at Modesto Community College.
- October 2010 – Greg Delory gave a talk about water on the Moon to 100 teachers of all grade levels at the California Science Education Conference.
- January 2011- Bill Farrell gave a presentation on DREAM to 5 students at Seton-Keough High School in Baltimore, MD as part of the DREAM Lunar Extreme Program.
- January 2011 – Bill Farrell gave a presentation on DREAM to 5 students at Eleanor Roosevelt High School in Greenbelt, MD as part of the DREAM Lunar Extreme Program.
- February 2011 – Nick Gross gave a presentation to 5 students and 1 teacher at Eleanor Roosevelt High School in Greenbelt, MD.
- February 2011 – Nick Gross gave a presentation to 5 students and 1 teacher at Seton-Keough High School in Baltimore, MD.

C. Outreach Events

The DREAM team is committed to sharing the excitement of its research with students and the general public through a variety of means, including participation in large outreach events. Participation in such events allows the team to reach a large number of people and to provide them with a perspective of the Moon and lunar science with which they may not be familiar. It also provides an opportunity to engage the general public in one-on-one discussion.

Maryland Day

The DREAM team has participated in a variety of outreach events over the first two program years, including hosting a hands-on exhibit at “Maryland Day” at the University of Maryland on April 24, 2010. Approximately seventy-five thousand members of the public, representing a range of age groups, were in attendance.

At this event, DREAM team members led the public through an experiment to simulate triboelectric charging of dust and its adherence to astronaut space suits on the lunar surface. Balloons were used to represent an astronaut moving around on the lunar surface, while salt represented lunar dust. Participants were encouraged to rub the balloon on their clothing, which caused the balloons to become negatively charged. By holding the balloons close to a small pile of salt on a tabletop, the salt became positively charged via induction and was therefore attracted to the balloon. A “clicker” electrometer was used to indicate the presence of an electric field. Team members used this activity to have a discussion with visitors to the exhibit about how and why dust clings to astronaut suits and other equipment, why it is of concern, and what can be done to assess and remedy the effects. The team also displayed a poster about DREAM’s science goals and handed out NLSI brochures, stickers, and Moon lithos.

International Observe the Moon Night

The DREAM team has participated in a variety of outreach events over its two program years, including International Observe the Moon Night (InOMN) on September 18, 2010, at the NASA Goddard Visitor Center. Approximately 500 members of the public, representing a range of age groups, were in attendance. At this event, DREAM team members contributed to Goddard’s InOMN event in a number of ways. Bill Farrell volunteered at the “Chat with a Scientist” table where he engaged the public in conversations about the Moon, DREAM’s science goals, his other scientific interests, and his career path. Jacob Bleacher also shared his experiences as a scientist at the “Chat with a Scientist” table. Tim Stubbs created a variety of visuals for use at the “Seeing the Moon in a Whole New Light” table, including an image of how the Moon would appear in the night sky on September 18, a map of shadow depth on the night side of the Moon, a map showing the amount of sunlight predicted to reach the surface of the Moon during InOMN, and the location of the Moon relative to the Earth on September 18. Noah Petro gave a public lecture to InOMN participants on the Moon and lunar exploration. Lora Bleacher, Andrea Jones, and Brooke Hsu coordinated and assisted in implementing the Goddard InOMN event and the greater InOMN effort.

Appendix 1: DREAM Science Publications and Presentations

A. DREAM Papers (under review, in press, published)

Sarantos, M., R. M. Killen, A. S. Sharma and J. A. Slavin (2010), Sources of sodium in the lunar exosphere: Modeling using ground-based observations of sodium emission and spacecraft data of the plasma, *Icarus* 205, p. 364-374.

Killen, R.M., A.E.Potter, D.M. Hurley, C. Plymate, S. Naidu, (2010). Observations of the LCROSS Event from the McMath_Pierce Solar Telescope: Sodium and Dust. *NOAO/NSO Newsletter*, 101,8

Farrell, W. M. , T. J. Stubbs, J. S. Halekas, R. M. Killen, G. T. Delory, M. R. Collier, R. R. Vondrak (2010), The anticipated electrical environment within permanently shadowed lunar crater, *J. Geophys. Res.,* 115, E03004, doi:10.1029/2009JE003464.

Stubbs, T. J., D. A. Glenar, A. Colaprete, and D. T. Richard (2010), Optical scattering processes observed at the Moon: Predictions for the LADEE Ultraviolet Spectrometer, *Planet. Space Sci.*, 58, 830, doi:10.1016/j.pss.2010.01.002.

Roberson, I. P., S. Sembay, T. J. Stubbs, K. D. Kuntz, M. R. Collier, T. E. Cravens, S. L. Snowden, H. K. Hills, F. S. Porter, P. Travnicek, J. A. Carter, and A. M. Read, (2009), Solar wind charge exchange observed through the lunar exosphere, *Geophys. Res.Lett., 36,* L21102, doi:10.1029/2009GL040834.

Killen, R.M., et al., , (2011), Observations of the impact plume from the LCROSS event, *Geophys. Res. Lett,* . 37, L23201.

Stubbs, T. J, , D. A. Glenar, M. R. Collier, W. M. Farrell, J. S. Halekas, G. T. Delory, and R. R. Vondrak, (2010), On the Role of Dust in the Lunar Ionosphere, Geophys. Res. Lett., submitted, 2011GL047049.

Halekas, J. S., Y. Saito, G. T. Delory, and W. M. Farrell (2010), New view of the lunar plasma environment, *Planet. Space Sci.,* in press, doi:10.1016/j.pss.2010.08.011

Richard, D. T., D. A. Glenar, T. J. Stubbs, S. S. Davis, A. Colaprete (2010), Light scattering by complex dust grains in the lunar environment: towards a taxonomy of models for real grain scattering behavior, *Planet. Space Sci.,* in press, doi:10.1016/j.pss.2011.01.003.

Glenar, D. A., T. J. Stubbs, J. E. McCoy, R. R. Vondrak (2010), A Reanalysis of the Apollo Light Scattering Observations, and Implications for Lunar Exospheric Dust, *Planet. Space Sci.,* in press.

Collier, M. R., K. Hills, T. J. Stubbs, J. S. Halekas, G. T. Delory, J. Espley, W. M. Farrell, J. W. Freeman, and R. R. Vondrak, Lunar Surface Electric Potential Changes Associated with Traversals of the Terrestrial Bow Shock, *Planet. Space Sci.,* in press.

Marshall, J. R. , D. Richard, S. Davis, Electrical stress and strain in lunar regolith, Planet. Space Sci., in press.

Jackson, T. L., W. M. Farrell, G. T. Delory, J. S. Halekas, T. J. Stubbs, R. M. Killen (2010), The Discharging of Roving Objects in the Lunar Polar, *J. Spacecraft Rockets*, in press.

Halekas, J. S., V. Angelopoulos, D.G. Sibeck, K.K. Khurana, C.T. Russell, G.T. Delory, W.M. Farrell, J.P. McFadden, J.W. Bonnell, D. Larson, R.E. Ergun, F. Plaschke, K.H. Glassmeier (2011), First results from ARTEMIS, a new two-spacecraft lunar mission: Counter-streaming plasma populations in the lunar wake, *Space Sci. Rev.*, in press, doi:10.1007/s11214-010-9738-8.

Colaprete, A., et al. (2010), Detection of water in the LCROSS ejection plume, Science, 330, 463.

Poppe, A, J. S. Halekas, M. Horanyi (2010), Negative potentials above the day-side lunar surface in the terrestrial plasma sheet: evidence of non-monotonic potentials, *Geophys. Res. Lett.* , 405 *38*, doi:10.1029/2010GL046119.

Hurley, D. H. , R.M. Killen, A.E. Potter, C. Plymate and S. Naidu Observations and modeling of the lunar impact plume from the LCROSS Event. *Geophys. Res. Lett*., In press, 2010.

Gladstone, G.R., D.M. Hurley, K.D. Retherford, P.D. Feldman, W.R. Pryor, + the LAMP Team, LRO-LAMP Observations of the LCROSS Impact Plume, *Science* 330, 472, 2010

Hodges, R. R. (2010), Resolution of the lunar hydrogen enigma, Geophys. Res. Lett., in press.

Halekas, J. S., A. Poppe, G. T. Delory, W. M. Farrell, M. Horanyi (2010), Solar wind electron interaction with the dayside lunar surface and crustal magnetic fields: Evidence for precursor effects, *Earth Planets & Space.* , submitted.

Halekas, J. S., G.T. Delory, W.M. Farrell, V. Angelopoulos, J.P. McFadden, J.W. Bonnell, M.O., Fillingim, F. Plaschke (2011), First remote measurements of lunar surface charging from ARTEMIS: Evidence for non-monotonic sheath potentials above the dayside surface, *J. Geophys. Res.*, Submitted.

Sarantos, M., R. M. Killen, D. A. Glenar, M. Benna, and T. J. Stubbs, Metallic species, oxygen and silicon in the lunar exosphere: upper limits and prospects for LADEE measurements, *Icarus*, submitted, 2010.

Wiehle, S., F. Plaschke, U. Motschmann, K.-H. Glassmeier, H.U. Auster, V. Angelopoulos, J. Mueller, H. Kriegel, E. Georgescu, J. Halekas, D.G. Sibeck, J.P. McFadden, First lunar wake passage of ARTEMIS: Discrimination of wake effects and solar wind fluctuations by 3d hybrid simulations, *Planet. Space Sci*., in press, doi: 10.1016/j.pss.2011.01.012, 2011.

B.DREAM Conference/Seminar Presentations (up to 022311)

Angelopoulos, V., J.S. Halekas, D.G. Sibeck, J. McFadden, F. Plaschke, J. Bonnell, G.T. Delory, R. Lillis, K. Khurana, C.T. Russell, The ARTEMIS mission and first results, P22A-01, *Western Pacific Geophysics Meeting*, 2010.

Angelopoulos, V. , R. Lillis, D.G. Sibeck, J. Halekas, G.T. Delory, K.K. Khurana, C.T. Russell, J.P. McFadden, J. Bonnell, D. Larson (2010), ARTEMIS, a two spacecraft, planetary and heliophysics lunar mission, 41st Lunar and Planetary Science Conference, id: 1425, 2010.

Bleacher L.V., Weir H., Gross N., Farrell W.M. (2009) Dynamic Response of the Environment at the Moon (DREAM): Engaging students, teachers, and the public in learning about the solar-lunar connection. Lunar Sci. Forum II, NASA Lunar Sci. Inst. (abstr.)

Bleacher L.V., Weir H., Twu Y., Farrell W.M., Gross N. (2009) Dynamic Response of the Environment at the Moon (DREAM): Providing opportunities for students and teachers to learn about the solar-lunar environmental connection. Eos Trans. AGU, 90(52), Fall Meet. Suppl., Abstract ED41A-0521

Bleacher L.V., Weir H., Farrell W.M., Gross N. (2010) Dynamic Response of the Environment at the Moon (DREAM): Opportunities for students and teachers to learn about the solar-lunar environmental connection. Lunar Sci. Forum II, NASA Lunar Sci. Inst. (abstr.)

Collier, M. R., H.K. Hills, J. Halekas, W.M. Farrell, G.T. Delory, J.Espley, J.W. Freeman, R. Vondrak, J. Kasper (2009) , Lunar surface potentialincreases during terrestrial bow shock traversals, Lunar Science Forum, 2009.

Collier, M. R. , T.J. Stubbs, H.K. Hills, J.S. Halekas, W.M. Farrell, G.T. Delory, J.R. Espley, J.W. Freeman, R.R. Vondrak (2010), Lunar surface potential changes associated with foreshock energetic electrons, Lunar Science Forum 2010.

Collier, M. R., H.K. Hills, T.J. Stubbs, J.S. Halekas, G.T. Delory, J. Espley, W.M. Farrell, J.W. Freeman, R. Vondrak (2010), Lunar surface potentials associated with traversals of the terrestrial bow shock, Lunar Dust, Plasma & Atmosphere: The Next Steps, 2010.

Farrell, W. M., DREAM: Dynamic Response of the Environment at the Moon (2009), NASA/GSFC's Lunar Exploration and Science Working Group (LESWG), May 22, 2009

Farrell, W. M., G. Delory, R. Killen, J. Halekas, S. Bale, D. Krauss-Varban, R. Vondrak, M. Collier, J. Keller, T. Jackson, R. Hartle, M. Hesse, M. Sarantos, R. Elphic, T. Colaprete, T. Stubbs, D. Hurley, J. Marshall, R. Hodges, D. Glenar, W. Paterson, H. Spence, L.

Bleacher, H. Weir, M. Horanyi, M. Dube, M. Hyatt, J. Kasper, Y. Saito (2009), Dynamic response of the environment at the Moon (DREAM): A NLSI team exploring the solar-lunar connection, Lunar Science Forum 2009.

Farrell, W. M. T.J. Stubbs, J.S. Halekas, G.T. Delory, M.R. Collier, R.R. Vondrak (2009), The anticipated electrical environment within permanently shadowed lunar craters, Lunar Science Forum 2009.

Farrell, W.M., J. S. Halekas, T. J. Stubbs, G. T. Delory, R. M. Killen, M. R. Collier, R. R. Vondrak, T. L. Jackson and NLSI DREAM team (2010), Plasma Flow Past an Obstacle: Advances Derived from Lunar Applications, Lunar Dust, Atmosphere, and Plasma: The Next Steps, Jan 28, 2010.

Farrell, W. M., R. M. Killen, G. T. Delory,T. J. Stubbs, Y. Wang, M. Collier, LRO/LOLA team and NLSI DREAM team (2010), THE CASE FOR REACTIVE SURFACE GEOCHEMISTRY AT THE MOON, 41st Lunar Planetary Science Conference, Mar 2, 2010

Farrell, W. M., DREAM: Dynamic Response of the Environment at the Moon, NASA/Goddard Space Flight Center SED Director's Seminar, May 26, 2010

Farrell, W. M., Lunar Dust, Exosphere, and Plasma: Our DREAM Science, LRO EPO Forum, July 15, 2010

Farrell, W. M., R. M. Killen , G. T. Delory, T. J. Stubbs, M. R. Collier, A. Colaprete, J.-E. Wahlund, M. W. Morooka, M. Shafiq, W. S. Kurth, D. A. Gurnett, NLSI DREAM team and Cassini RPWS team, Lunar impact debris plume: Is the Enceladus plume a reasonable analog?, Lunar Science Forum 2010, July 20, 2010.

Farrell, W. M., T.J.W. Lazio, T.J. Stubbs, R.J. McDowell, J.O. Burns, J.S. Halekas, Lunar environmental effects and astrophysical platforms, Lunar Science Forum, 2010.

Farrell, W. M., R. M. Killen, and G. T. Delory, DREAM and its support of LADEE, NASA/Goddard Space Flight Center SED Director's Seminar, Aug 25, 2010.

Farrell, W. M., T. L. Jackson, J. S. Halekas, T. J. Stubbs, G. T. Delory, R. M. Killen, M. R. Collier, R. R. Vondrak, and DREAM LSI team, Are there electrical hazards associated with operations in the lunar polar region?, LEAG2010 Meeting, Sept 14 2010

Farrell, W.M., T.J. Stubbs, T.L. Jackson, A. Colaprete, J.L. Heldman, P.H. Schultz, R.M. Killen, G.T. Delory, J.S. Halekas, J.L. Marshall, M.I. Zimmerman, M.R. Collier, and R.R. Vondrak, Electrical evolution of a dust plume from a low energy lunar impact: A model analog to LCROSS. 42nd LPSC, 2011.

Farrell, W.M., R.M. Killen, R.R. Vondrak, D.M. Hurley, T.J. Stubbs, Could lunar polar ice be a "fountain" source for the dayside water veneer?, 42nd LPSC, 2011.

Fillingim, M.O., G.T. Delory, J.S. Halekas, R.E. Grimm, Signal strength and bandwidth for magnetotelluric sounding of the interior of the Moon, *Fall AGU*, Talk DI43A-1944, 2010.

Glenar, D. A., T. J. Stubbs, R. Vondrak (2009), A Reanalysis of Apollo Light Scattering Observations, and Implications for the Distribution of Lunar Exospheric Dust, Eos Trans. AGU, 90(52), Fall Meet. Suppl., Abstract P23C-1264.

Glenar, D. A., T. J. Stubbs, R. Vondrak, J. McCoy (2010), A Reanalysis of Apollo Light Scattering Observations: Implications for the Distribution of Lunar Exospheric Dust, *Lunar Dust, Plasma and Atmosphere: The next Steps*, 2010, Jan, Boulder.

Glenar, D. A., T. J. Stubbs, J. Hahn , R. Vondrak (2010). Did Clementine Observe Lunar Horizon Glow? *Proc. 41st LPSC*, paper # 2735.

Glenar, D. A., T. J. Stubbs, J. Hahn, and R. R. Vondrak (2010), Did Clementine Observe Lunar Horizon Glow?, P51C-1457, presented at the *2010 Fall AGU meeting*, American Geophysical Union, San Francisco, CA, December 13–17.

Glenar, D. A., T. J. Stubbs, A. Colaprete, D. T. Richard, and G. T. Delory (2009), Optical scattering processes observed at the Moon: Predictions for the LADEE Ultraviolet/Visible Spectrometer, presented at the *2nd Annual Lunar Science Forum*, NASA Lunar Science Institute, NASA Ames Research Center, Moffett Field, CA, July 21–23.

Glenar, D. A., T. J. Stubbs, and R. R. Vondrak (2009), A reanalysis of Apollo light scattering observations: Implications for the spatial distribution of lunar exospheric dust, presented at the *2nd Annual Lunar Science Forum*, NASA Lunar Science Institute, NASA Ames Research Center, Moffett Field, CA, July 21–23.

Halekas, J. S, G. Delory, S. Bale, D. Krauss-Varban, R. Lin, W. Farrell,The dynamic lunar wake, Lunar Science Forum, 2009.

Halekas, J. S., V. Angelopoulos, D.G. Sibeck, K. Khurana, C.T. Russell, Delory, G. T. J.P. McFadden, J.W. Bonnell, D. Larson, First results from ARTEMIS, a new two-spacecraft lunar mission, Lunar Science Forum, 2010.

Halekas, J. S, G.T. Delory, A. Poppe, M. Horányi, Probing the dayside lunar surface-plasma interface in the solar wind, Lunar Science Forum, 2010.

Halekas, J. S., The lunar space plasma environment, INVITED, Lunar Media Workshop, 2010.

Halekas, J.S, The Moon as a plasma laboratory, INVITED, Lunar Media Workshop, 2010.

Halekas, J. S., ARTEMIS Senior Review, INVITED, 2010.
V. Angelopoulos, J.S. Halekas, D.G. Sibeck, J. McFadden, F. Plaschke, J. Bonnell, G.T. Delory, R. Lillis, K. Khurana, C.T. Russell, The ARTEMIS mission and first results, P22A-01, Western Pacific Geophysics Meeting, 2010.

Halekas, J. S., G.T. Delory, R.P. Lin, W.M. Farrell, Anomalous electron entry into the lunar wake, P23A-045, Western Pacific Geophysics Meeting, 2010.

Halekas, J. S., The space interaction environment of the Moon, P31B-01, INVITED, Western Pacific Geophysics Meeting, 2010.

Halekas, J. S, G.T. Delory, R.P. Lin, W.M. Farrell, T.J. Stubbs, M.R. Collier, Lunar surface charging: Current understanding and next steps, Lunar Dust, Plasma & Atmosphere: The Next Steps, 2010.

Halekas, J. S., V. Angelopoulos, D.G. Sibeck, K. Khurana, C.T. Russell, G.T. Delory, J.P. McFadden, J.W. Bonnell, D. Larson, Lunar plasma and exospheric science from ARTEMIS, INVITED, Lunar Dust, Plasma & Atmosphere: The Next Steps, 2010.

Halekas, J.S. Interaction regions near the Moon and other non-magnetized small bodies, *5th Alfven Conference*, 2010.

Halekas, J. S., G. T. Delory, T. J. Stubbs, W. M. Farrell, and R. P. Lin (2009), Developing a predictive capability for lunar surface charging during solar energetic particle events, #1357, presented at the *Lunar and Planetary Science Conference XL*, Lunar and Planetary Institute, Houston, TX, March 23–27.

Hartle, R. E, M. Sarantos, R.M. Killen, E.C. Sittler, J.S. Halekas, S. Yokota, Y. Saito, W. Farrell, Lunar neutral exosphere properties from pickup ion analysis, Fall AGU, Talk P23C-1266, 2009.
Hurley, D.M., R. Gladstone, K. Retherford, S. Stern, J. Parker, D. Kaufmann, A. Egan, M. Davis, M. Versteeg, D. Slater, P. Miles, A. Steffl, T. Greathouse, P. Feldman, W. Pryor, A. Hendriz, R. Killen, and A. Potter, Modeling the Vapor Plume Expansion Resulting form the LCROSS Impact on the Moon, 41st LPSC, Abstract # 2308, Houston, Texas, 2010.

Hurley, D. M. "Lunar Volatile Transport and Segregation" University of California Berkeley Space Science Laboratory seminar, July 2009

Hurley, D. M. "Current Understanding of Lunar Volatile Transport and Segregation," Lunar Reconnaissance Orbiter Targeting Meeting, Arizona State University, June 2009.

Hurley, D. M. The Lunar Surface-Atmosphere Interaction and Its Effect on Atmospheric Distribution, LSI conference, NASA Ames Research Center, July 2009

Hurley, D. "Surficial OH/H2O on the Moon: Modeling Delivery, Redistribution, and Loss," Lunar And Planetary Science Conference, #1844, The Woodlands, TX, March 2010.

Hurley, D.M. "Modeling the Production, Delivery, and Maintenance of OH/H2O on the Lunar Surface", Lunar Science Forum, Mountain View, CA, July 2010

Jackson T. L., W.M. Farrell, G.T. Delory, T.J. Stubbs, M.R. Collier, J.S. Halekas, R.R. Vondrak, Astronaut and object charging on the lunar surface, 41st Lunar and Planetary Science Conference, id: 2368, 2010.

Jackson, T. L., W.M. Farrell, G.T. Delory, T.J. Stubbs, M.R. Collier, J.S. Halekas, R.R. Vondrak, Astronaut and object charging on the lunar surface, Lunar Dust, Plasma & Atmosphere: The Next Steps, 2010.

Keller, J.W., R.M. Killen, T.J. Stubbs, W.M. Farrell, and J.S. Halekas, Magnetically controlled ion processing: A Possible explanation for swirls at Reiner Gamma. 42nd LPSC, 2011.

Killen, R.M., A.E. Potter, D.M. Hurley, C. Plymate, S. Naidu, Observations of the LCROSS Impact event from the McMath-Pierce Solar Telescope: Sodium and Dust, 41st LPSC, abstract 2333, Houston, Texas, 2010.

Killen, R. M., ;M. Sarantos; J. S. Halekas; R. E. Hartle; D. M. Hurley (2010), The Neutral Lunar Exosphere as a Source for Pickup Ions. AGU Fall Meeting 2010, P42A-04.

Krzykowski, M. (2010), Identifying and characterizing VxB events from the Suprathermal Ion Detector Experiment (SIDE) of the Apollo 14 Mission, Undergraduate Women in Physics, Lincoln, NE.

Lin, R. P. and J. Halekas, Solar wind and terrestrial magnetospheric plasma interactions with the Moon, Lunar Dust, Plasma & Atmosphere: The Next Steps, 2010.

Mahaffy, P., R. Hodges (2010), The lunar atmosphere: Next steps, Lunar Dust, Plasma & Atmosphere: The Next Steps, 2010.

Marshall, J. R., D. Richard, S. Davis, A. Colaprete, Dust lofting mechanisms on the Moon, Lunar Dust, Plasma & Atmosphere: The Next Steps, 2010.

Plymate C., T. H. Morgan, R. M. Killen, and A. E. Potter A Concept for Small, Remotely Operated, Coronagraph located at Small Observatory Designed for Frequent, Low-cost Remote Observations of the Lunar Exosphere, DPS Abstract, 2010.

Poppe, A.R., J.S. Halekas, M. Horanyi, Non-monotonic potentials above the lunar surface: Implications for electron reflectometry measurements, *Fall AGU*, Talk P54B-08, 2010.

Poppe, A., J.S. Halekas, M. Horanyi, Simulations of the near-surface lunar plasma environment: Implications for electron reflectometry measurements of the lunar surface potential, *5th Alfven Conference*, 2010.

Richard D. T., Glenar D. A., Davis S.S., Stubbs T. J., Colaprete A., "Modeling of light scattering by non-spherical lunar dust grains", Lunar Science Forum 2010, July 20-22, 2010, at the NASA Ames Conference Center, Moffett Field, California .

Richard D. T., Glenar D. A., Stubbs T. J., Davis S. S., Colaprete A., "Light Scattering in the Lunar Orbital Environment by Non-Spherical Dust Grains", 41th Lunar and Planetary Science Conference, (Lunar and Planetary Science XXXXI), The Woodlands, Texas. LPI Contribution No.2704, March 1-5, 2010.

Richard D. T., Glenar D. A., Davis S. S., Stubbs T. J., Colaprete A., "Modeling of light scattering by non-spherical lunar dust grains", Lunar Dust, Plasma and Atmopshere: The Next Steps, Boulder, Colorado, January 27-29 2010.

Richard, D. T., Glenar, D. A., Stubbs, T. J., Davis, S. S., Colaprete, A., "'But still, like dust, I'll rise' Modeling the Scattering Signature of Lunar Dust for the Lunar Atmosphere and Dust Environment Explorer", NASA Lunar Science Institute Forum, NASA Ames Research Center, July 2009.

Rivkin, A., J. M. Sunshine, D. T. Blewett, D. M. Hurley, and C. A. Hibbitts. "Lunar Water, Asteroidal Observations: Implications and Opportunity" Lunar And Planetary Science Conference, #1088, The Woodlands, TX, March 2010.

Sarantos, M., R. M. Killen, D. Glenar, T. J. Stubbs (2010). Prospects for the Detectability of Lunar Exospheric Refractories by LADEE Ultraviolet-Visible Measurements, *2010 LEAG Annual Meeting*, Wash. DC.

Sarantos, M.; Killen, R. M.; Benna, M.; Hartle, R.; , The lunar exosphere: expectations for LADEE measurements.Geophysical Research Abstracts,Vol. 11, EGU2009-11812, 2009, EGU General Assembly 2009

Sarantos, M., R Killen, R Hartle, M Benna, A. Surjalal Sharma, The Lunar Exosphere: observations, models, and expectations for LADEE measurements, NASA 2009 Lunar Science Forum

Sarantos, M., R. M. Killen, D. A. Glenar, M. Benna, and T. J. Stubbs (2010), Metallic species, oxygen and silicon in the lunar exosphere: some prospects for LADEE measurements, presented at the *3rd NASA Lunar Science Forum*, NASA Lunar Science Institute, NASA Ames Research Center, Moffett Field, CA, July 20–22.

Sarantos, M., Killen, R., Benna, M., Glenar, D., Stubbs, T.. Detectability of lunar exospheric constituents: simulations for LADEE, Geophysical Research AbstractsVol. 12, EGU2010-14572, 2010,EGU General Assembly 2010

Sarantos, M., R. M. Killen, D. A. Glenar, M. Benna, and T. J. Stubbs (2010), Metallic species, oxygen and silicon in the lunar exosphere: constraints from Mercury and prospects for LADEE measurements, P51C-1456, presented at the *2010 Fall AGU meeting*, American Geophysical Union, San Francisco, CA, December 13–17.

Stubbs, T. J, D.A. Glenar, M.R. Collier, W.M. Farrell, J.S. Halekas, G.T. Delory, R.R. Vondrak, On the role of dust in the lunar exo-ionosphere, Fall AGU, Talk P23C-1265, 2009.

Stubbs, T. J. (2009), Planetary Science Update: NLSI and Future Lunar Missions, Lunar Airborne Dust Toxicity Assessment Group, Houston TX.

Stubbs, T. J, D. Glenar, M. Collier, W. Farrell, J. Halekas, G. Delory, R. Vondrak, On the possible role of dust in the lunar ionosphere, Lunar Science Forum, 2009.

Stubbs, T. J., D. A. Glenar, M. R. Collier, W. Farrell, J. S. Halekas, G. T. Delory, R. R. Vondrak (2009), A Reanalysis of Apollo Light Scattering Observations, and Implications for the Distribution of Lunar Exospheric Dust, Eos Trans. AGU, 90(52), Fall Meet. Suppl., Abstract P23C-1265.

Stubbs, T.J., Y. Wang, W.M. Farrell, J.S. Halekas, R.R. Vondrak, E. Mazarico, G.A. Neumann, D.E. Smith, M.T. Zuber, M.H. Torrence, Characterizing the plasma shadowing and surface charging at the Moon using LOLA topographic data: Predictions for the LCROSS impact, 41st Lunar and Planetary Science Conference, id: 2658, 2010.

Stubbs, T. J., Y. Wang, E. Mazarico, G. A. Neumann, D. E. Smith, M. T. Zuber, and M. H. Torrence (2010), Characterizing the optical shadowing at the Moon using LOLA topographic data: Predictions for the LCROSS impact, #2410, presented at the *41st Lunar and Planetary Science Conference*, Lunar and Planetary Institute, The Woodlands, TX, March 1–5.

Stubbs, T. J., Y. Wang, E. Mazarico, G. A. Neumann, D. E. Smith, M. T. Zuber, and M. H. Torrence (2010), Characterizing the optical and plasma shadowing at the Moon using a LOLA digital elevation model, presented at the *First Workshop on Lunar Dust, Plasma and Atmosphere: The Next Steps*, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, January 27–29.

Stubbs T. J, , D. Glenar, M. Collier, W. Farrell, J. Halekas, G. Delory, R. Vondrak, On the role of dust in the lunar ionosphere, Lunar Dust, Plasma & Atmosphere: The Next Steps, 2010.

Stubbs T. J, W.M. Farrell, J.S. Halekas, G.T. Delory, M. Collier, R. Vondrak, Lunar surface charging in the magnetotail, P23A-047, Western Pacific Geophysics Meeting, 2010.

Stubbs T. J., W. M. Farrell, M. R. Collier, D. Glenar, D. T. Richard, T. L. Jackson, R. M. Killen, M. Sarantos, G. T. Delory, J. S. Halekas and R. R. Vondrak (2010). Acquiring "Ground Truth" About the Dynamic Lunar Environment: Implications for Science and Exploration,*2010 LEAG Annual Meeting*, Wash. DC.

Stubbs, T. J. (2010), Exploring Vesta, *Lunar Exploration Science Working Group*, NASA Goddard Space Flight Center, Greenbelt, MD, February 18.

Stubbs, T. J. , W. M. Farrell, M. R. Collier, and R. R. Vondrak (2010), Does the Surface of the Moon Really Charge to Extreme Positive Potentials in the Magnetotail Lobes? A Re-analysis of Apollo/CPLEE observations, P51C-1458, presented at the *2010 Fall AGU meeting*, American Geophysical Union, San Francisco, CA, December 13–17.

Stubbs, T. J., W. M. Farrell, J. S. Halekas, G. T. Delory, M. R. Collier, and R. R. Vondrak (2010), Lunar surface charging in the Earth's distant magnetotail, presented at the *3rd NASA Lunar Science Forum*, NASA Lunar Science Institute, NASA Ames Research Center, Moffett Field, CA, July 20–22.

Stubbs, T. J., D. A. Glenar, D. T. Richard, and A. Colaprete (2009), Predictions for the optical scattering at the Moon, as observed by the LADEE UV/VIS spectrometer, #2348, presented at the *Lunar and Planetary Science Conference XL*, Lunar and Planetary Institute, Houston, TX, March 23–27.

Tao, J., R.E. Ergun, L. Andersson, V. Angelopoulos, J.W. Bonnell, D.L. Newman, J.P. McFadden, J.S. Halekas, C.M. Cully, K. Glassmeier, A. Roux, O. Lecontel, D.E. Larson, W. Baumjohann, M.V. Goldman, H. Auster, Results from the first lunar-wake flyby of ARTEMIS on wake potential, electron beams, and electrostatic waves, *Fall AGU*, Talk SH51D-1700, 2010.

Appendix 2: Lunar Explorer Mission Line White Paper (Draft)

Summary: A draft (3/25/2010) of a proposed Lunar Explorer mission line white paper being developed during PY 1 and 2 of DREAM as a joint DREAM/CCLDS effort. The concept was presented at the LDAP 2010 workshop in Jan 2010 and at the Lunar Science Forum in 2011. With the advent of ESMD's xScout program, the LE mission line was dropped. xScouts included all of the primary points of LE including PI-class missions, quick response, and flights every 2 years. The LE white paper is enclosed, lead by DREAM's W. Farrell & G. Delory, and CCLDS's PI M. Horanyi.

A Lunar Explorer (LE) Mission Line: Providing Consistent Access to the Moon

A White Paper presented by NASA's Lunar Science Institute

Motivation

We come to learn by way of the recent LCROSS low cost Class D mission that large amounts of water – 7% by weight - may be collecting within lunar polar traps. A Mission of Opportunity instrument, M-cubed, on a low cost orbiter provided by an international partner, Chandrayaan-1**,** found that water may also continually collect near the lunar terminator region. As a consequence of these missions, the Moon is no longer view by the science community and the general public in the same way. Both of these game-changing observations are derived from a set of PI-class endeavors.

Unfortunately, the current Lunar Quest mission line covers the LADEE explorer to be launched in 2013 and the International Network Lander (ILN) system to be landed closer 2018. However, there is a substantial temporal gap between the two missions. Further, any delays in the build of the multi-spacecraft ILN will further limit access to the Moon to capitalize on these recent discoveries. As it stands now, there is not an opportunity to advance the study of lunar chemistry and water (or any other highly relevant lunar science topic) until after 2020 – even though Space.com rated lunar water as the #1 space science discovery for 2009 (http://www.space.com/scienceastronomy/091228-best-space-science-2009.html).

To offset this delay in basic science return and enhance public interest, NASA's Lunar Science Institute (as a representative of the lunar community) suggests an addition to the Lunar Quest line – adding a new program called the Lunar Explorer (LE) program. This program would be a component of the primary Lunar Quest line already in place. LE is specifically designed to provide low cost, consistent, PI-derived access to the Moon much like the successful SMEX program has provided to the Heliophysics and Astrophysics Divisions. The objective is to use the program to go after lower-risk ‘low hanging’ science fruit that is now readily apparent at the Moon. Further this line would continue uninterrupted by any technical delays in the more-sophisticated primary LQ line.

LE’s Primary Axioms

To be successful and maximize the consistency of the science return, the LE program has a set of guiding axioms consistent with the overarching theme of **accessibility** which include the following:

-Provide low cost missions, each slight more expensive than a SMEX

-Provide consistent, repeatable access to the Moon, every 2 years.

-Keep this program separate and distinct from the directed lunar mission line such that any technical delays/cost overrun in the primary line does not bleed into LE.

-Each LE mission is derived by a PI science team and selected based upon the merit of the proposed science, science implementation, mission implementation, management and mission cost. The PI team defines the mission, their desired center affiliation, spacecraft provider, etc.

-Each mission is assured at a Class D level, and every PI recognizes this class in proposing its unique mission. As such, there is an inherent limit to ‘buying down’ risk for a given mission. As further discussed below, this strategy may favor low-risk orbiting mission over higher risk landed mission. However, the Class D level provides more open access to the flight build by early career scientists and engineers and for payloads built by students.

-Maximize the use of lower cost Minotaur and Pegasus launches. LADEE is to be launched on a Minotaur from Wallops Flight Facility. GSFC flight dynamics team and UC Berkeley scientists teamed on an existence proof for a Pegasus launch into lunar orbit (Category 1 LuSIE SMEX proposal). Thus both lower cost options (and any other available) should be considered by any PI team.

To implement the axioms describe above, it is anticipated that the LE program addition will bump the overall LQ line by approximately $60-70M per year to a total of ~$190M annually. Every two years, there should be thus ~$120-140M to provide to a potential LE mission launch.

Why the Moon?

The lunar science community has been reinvigorated with the recent finding of water on the Moon- which suggests a possible chemically-active body that had not been previously envisioned. Even before the discoveries, the lunar community provided a large and coherent response to the Decadal study, presenting ~35 white papers on lunar science topics (comparable to the Mars community). The attendance at the Lunar Science Forum and LPSC is large & expanding. Clearly the science community is interested in the Moon and the general public is fascinated by these newly discovered processes, as suggested by the Space.com rating of 2009 space results.

The Moon is nearby, easily accessible, and so very different from the Earth. While both the Earth and Moon are exposed to the same level of space environmental influences, one slightly larger body is geologically active, has a thick atmosphere, has a protective magnetosphere, and teems with life. In contrast, the other slightly smaller body is geologically dormant, has the thinnest of atmospheres, lacks a large-scale magnetic field, and is devoid of life. The divergent habitability pathways for such similarly-exposed and comparatively-sized objects is actually somewhat unsettling – and the differences therein are very worthy of exploration.

The Moon itself is of great scientific interest since it contains the remaining record of the cataclysmic bombardment period near 3.7 Gya. At and under the surface, the asymmetric distribution of unaccomodated elements like Th suggests an unusual and unexplained differentiation in its magma ocean during formation. Also, the near-airless body is directly immersed in the harsh space environment which results in physical processes like space weathering, atom emission/exosphere formation, and space plasma modification via obstructing surfaces. Meteoroid impacts continually weather the surface and lift dust – possibly to anomalously high altitudes. The very recent discovery of water punctuates the previously stated fact that polar regions are very special environments (and recent M^3 results suggest that processes associated with these special regions may extend further in latitude than originally anticipated). The Moon may also be an ideal remote-sensing platform for making profound astrophysical observations.

However, our near-by Moon is a special target because it is a classic representative of the most numerous kind of body in our solar system – an exposed rocky body – similar to Mercury, Pluto, Triton, the numerous KBOs, and asteroids. As we discover processes at the Moon, we also extend our knowledge of the basic processes occurring at such remote objects – objects that are now a prime targets under the Flexible Path (FP). **As such, the Moon may be the scientific lynchpin that places all the upcoming measurements obtained by the Exploration robotic program in common context.** As we explore the named targets in the FP, overseeing groups like NLSI should work with EMD to verify that proper cross-comparing context exists across the proposed rocky-body targets. The planetary science community may never be given a chance to obtain such a closely-related, cross-comparing rocky-body data set.

Why Class D?

Given that the theme to the LE program is increased accessibility, it is strongly recommended that the mission assurance remain at a Class D level consistent with NASA's NPR 8705.4. The missions would thus be SMEX-class (a level down from a Discovery-class mission). There are multiple reasons for this choice: 1) reduce the inherent cost of sub-system builds, 2) reduce the cost of oversight and reviews, 3) increase the accessibility of hardware build to early career engineers and scientists, 4) increase the number of student-built payloads, 5) proposing PI will design a low risk approach in the overall mission knowing that large amounts of risk reduction and development funding is not available. In other words, the PIs are asked to go after the 'low hanging' fruit and leave more complicated science returns to LQ directed missions or Discovery mission lines.

The only downside to this approach is it may reduce the number (or effectively eliminate) surface-landed missions from the LE program, which by inherent difficulty and risk may not be considered Class-D. However, landed mission may enter into the program if it is demonstrated that the landed approach has already undergone a reduction to the risk via separate effort (i.e., landed system development paid for outside of LE line). For example, in the 2011 budget, the EMD program is to create a parallel and robust exploration development program, and a PI could develop and test a landed system in that program and then use the now low risk, developed, and tested landing system for LE. Furthermore, we should not underestimate the innovation of PI teams to find new and unique pathways to get to the surface in a cost and risk constrained environment. A good example of such innovation was the use of gas balloons in lieu of power decent as a (relatively) low-cost/low-risk alternative to land on Mars. As long as the PIs fully know the mission assurance and cost constraints a priori, and still receives a passing TMCO review, then a landed mission should be considered in LE. However, those proposals that rely on LE funds to develop landing systems might fall into higher TMCO risk categories. All proposing PIs should thus fully understand such risk when submitting their unique mission implementation sections.

An SMD and EMD collaboration?

The LE program can be considered a natural follow-on to the $80M LCROSS mission. While this low cost mission was funded via ESMD, its science result had a highly significant impact in both Exploration and Science/Planetary communities.

As such, LE could be a program creating a natural wedding of SMD and EMD. Given Exploration's new 2011 emphasis on robotic programs, a joint effort would be of maximum benefit to both SMD and EMD: the planetary science community has a number of high value targets for study and these targets could provide additional octane for EMD's new robotic lines. Furthermore, potential LE PI's could leverage EMD development funding for landed system to be used to buy down risk when proposing to LE.

LE Program Implementation

It is suggested that the LE program be initiated by a $1M concept study award phase in 2011, where the community is canvassed to submit white papers on possible LE mission concepts. The top 5-10 concepts are then awarded $100-200k to further advance the concept over the next 9-12 months. After concept submission, a workshop can be held where ideas are exchange.

The Mars Scout program had a tremendously successful concept study program along these same lines. The concept studies funded 10 awards with over 40 submissions – and clearly cemented the community advocacy for Mars Scout. In these concepts studies, the Phoenix mission concept using Mars01 lander was unveiled, a MAVEN-like mission was proposed. When the Mars community was directly solicited for mission ideas, exciting and innovative concepts were formulated that have shaped the Mars program for the last decade.

We anticipate a similar LE concept study period will create an equal amount of excitement and innovation. Such ideas could feed forward and stimulate the EMD tech programs. Note that as nearly as many Decadal study papers were submitted regarding the Moon to the Inner Planets subpanel as papers to the Mars subpanel indicating a very active lunar community – and this was before the M^3 and LCROSS findings of water on the Moon.

Example Notional Missions

In the last 15 years, there have been a number of PI-class small-scale orbiting missions to the Moon like those expected from a LE program line. Each of these missions have provided unique new findings and in some cases radically revised our view of the Moon. These include Clementine, Lunar Prospector, LCROSS, and now the dual-spacecraft ARTEMIS missions ($15M per THEMIS bus). We anticipate future LE missions could do the same. While a community-based concept study would reveal a large number of new and innovative approaches to lunar science, we suggest a few notional mission concepts herein.

-Water Search Mission: Fly M^3-like IR spectrometer with full 3 micron sensing, a UV/Vis system that can sense exospheric OH, and a dedicated Ion Mass Spectrometer that can detect weak in situ species. Orbiter at 50-100 km. Combined mass of payload: < 30 kg

-Dark Ages Astrophysics Mission: Fly a very stripped down spacecraft sub-system with a dipole E-field antenna and 25-100 MHz radio system. Spacecraft transits through the lunar farside will block terrestrial radio contamination and could allow a detection of weak absorption features in the cosmic radio background. The RF system will also have the capability to radio-probe (via riometry techniques) the lunar ionosphere. Orbiter at ~100 km. Payload mass: <10 kg

-Dust-derived Surface Composition Mission: If LADEE proves that surface dust is ejected or lofted to high altitudes, then the lunar surface can be analyzed from orbit using a dust composition system like that flown to the moons of the outer planet (icy dust from Enceladus has been analyzed by this method). Dust ejected from polar regions might reveal the hydrocarbon nature of any hydrated minerals. Orbiter at 50-100 km. Payload mass: < 20 kg

-Marker Gas Release Experiment: Given that a 1 kg sodium release from the LCROSS impact is visible from ground based telescopes [Killen et al., 2010], a purposeful release of a spectrally bright ‘marker’ gas in bulk above the Moon could occur in order to trace the path of the gas as it migrates about the lunar surface. Ground based telescopes and orbital assets could be combined to get a picture of the lunar exosphere as it evolves from a single point source.