DREAM

Dynamic Response of the Environment at the Moon

2012 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

5.1 DREAM 2012 Annual Report Executive Summary

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

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

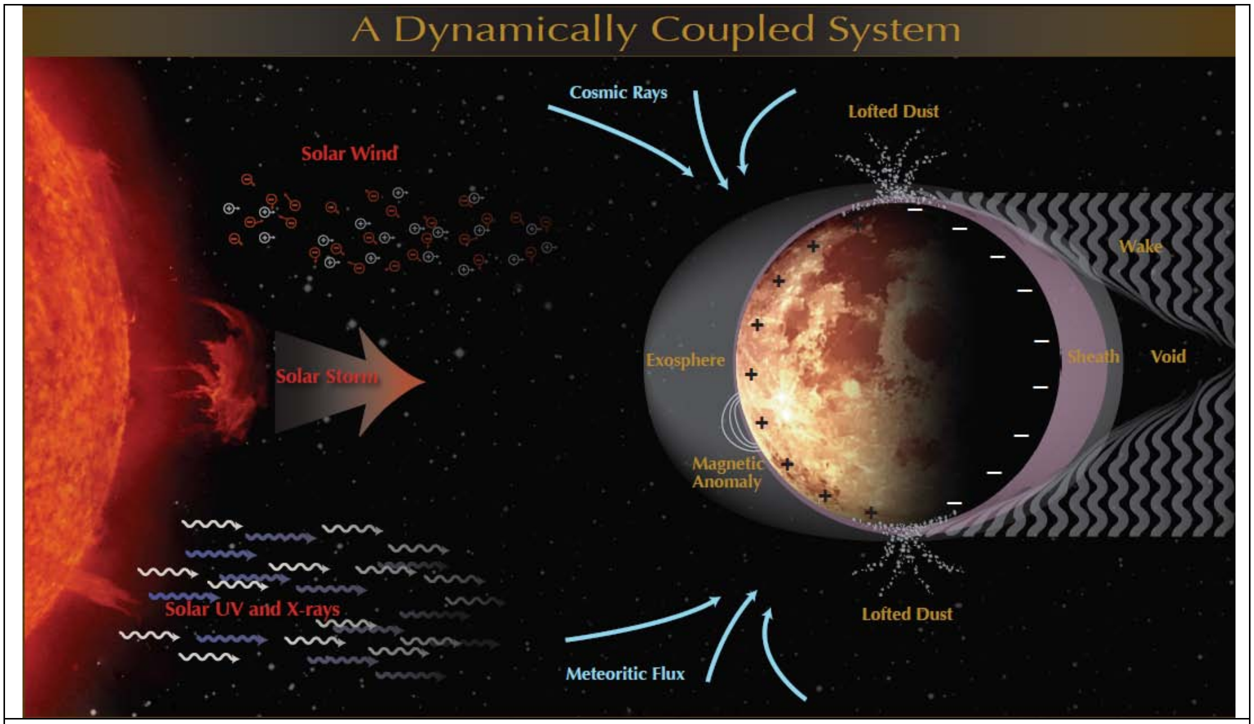

Figure ES.1: The solar-lunar connection studied by the DREAM lunar environment center

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

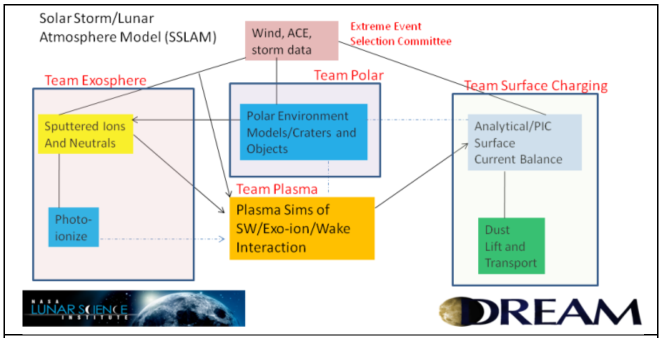

Figure ES.2 – Layout of the DREAM models used in the Solar Storm/Lunar Atmosphere Modeling (SSLAM) effort

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

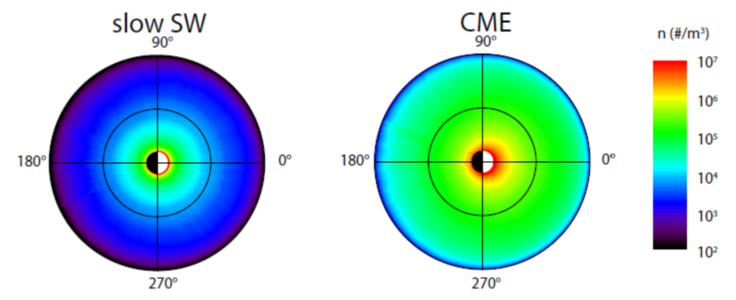

Figure ES.3- The enhancement in the sodium exosphere from CME sputtering (from Killen et al. 2012).

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

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

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

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

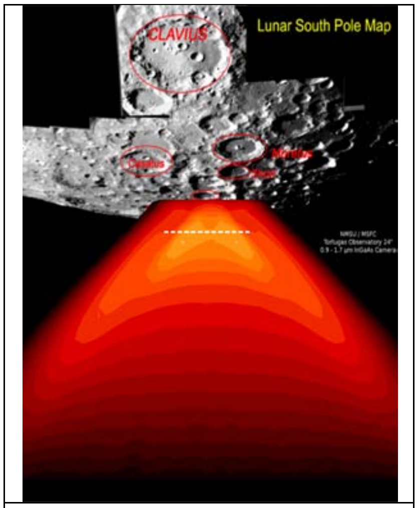

Figure ES.4- A model of the LCROSS sodium plume (Killen et al., 2010)

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

The observation campaign occurred during clear skies and was very fruitful, providing the only ground-based observation of the LCROSS impact. In fact, impact-ejected sodium from the bottom of Cabeus crater was observed to diffuse for up to 9 minutes after the impact. Comparing Monte Carlo models of the Na release (like Figure ES.4) to the telescopic observations suggest that the impact temperature for the species was near 1000K. This information provided critical and independent support to the LCROSS team who also arrived at a similar temperature.

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

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


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

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

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

DREAM

Dynamic Response of the Environment at the Moon

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

5.2 Advancement in the Understanding of the Neutral and Ion Exosphere

Objective Description. When the solar energy and matter interact with the lunar surface, the surface responds by emitting material – at the atomic and molecular level. This material comprises a solar-driven tenuous neutral gas about the Moon, called the exosphere. The atoms and molecules are of such low density that they collide with the surface rather than colliding with each other. As such, when accommodated, the atoms/molecules obtain an energy consistent with the surface temperature/surface energy. As such, this released lunar gas is often called a 'surface bounded exosphere'. However, the gas can be stimulated to high energies the allow atoms/molecules to escape the lunar gravity. Such energetic processes include sputtering and impact vaporization. **Both low energy and high energy process that allow release of volatile and refractory neutral species are all studied by the team subject-matter experts of the DREAM center**.

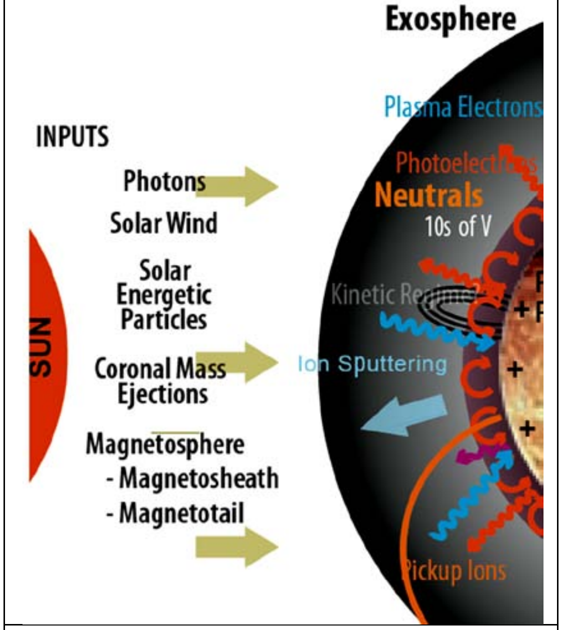

Figure 5.2.1 – The solar-driven lunar exosphere and exo-ionosphere

In 2009, the Moon Mineralogy Mapper (M-cubed) instrument on Chandrayaan-1 detected the presence of water and OH veneer at mid-latitudes, and there is the suggestion that this water is dynamic, possibly even manufactured by solar wind implantation. If the water and OH are dynamic, the should become part of the lunar exospheric system, creating a hydrosphere. DREAM team members have investigated this intriguing possibility, especially focusing on how such a dynamic water/OH system might be detected by the upcoming LADEE mission.

Relevancy. The broad objective of the DREAM exospheres group is to study the source and loss processes that affect volatiles on the moon. The details of these studies are widely relevant to many NAS/ Scientific Context for Exploration of the Moon SCEM themes: theme # 4 (lunar poles as special environments, #6 (impact processes), #7 (space weathering) and #8 (atmosphere-dust environment). We in fact study the changes in the lunar environment during solar extrema, solar storms at the Moon, and impacts. The fate of solar wind protons has been an intense focus in the past year, as controversy rages as to what fraction of protons are reflected, as both ions and neutrals, and what fraction engages in surface chemistry to form hydroxyl and water. This focus is directly related to the Heliophysics Science at the Moon (2007) report Theme # 1 (Plasma interactions and Environment). A second intense area of work has been the study of lunar polar volatiles (SCEM THEME #4). Inherent in the study of the source of lunar volatiles is space weathering: Theme # 2 (Weathering and Radiation). Finally**, the DREAM exospheric objectives connect directly to the recent Planetary Decadal Report (Vision & Voyages for Planetary Science, Nat. Acad. Press, 2011)** in the area of water and evolution of atmospheres [Theme #3] and basic physical and chemical processes at solar system objects [Theme #10].

State of Understanding Prior to DREAM. Prior to DREAM, the atmospheric composition of the Moon consisted of 5 species: Ar, He, Na, K, and possibly Rn (indirectly). The energetic portion of the sodium exosphere, at 1400K was not understood, and the view was that the Moon was dry –harboring little or no water or OH.

DREAM Advancements. During the past three years in which DREAM has been active, the basic paradigms concerning volatiles at the moon have been overturned. The Moon, once believed to be completely dry, is now known to have water (if not abundant water), and many other volatiles are known to be sequestered at the poles. An understanding of the extreme variability of the lunar exosphere has replaced the view that the exosphere is in steady state equilibrium, with thermal accommodation with the surface. Chemistry at the surface was formerly hinted at, but not modeled in detail. The response of the exosphere to variability in the solar wind was scoffed at. The following described in detail some of the key DREAM advancements made in its first three years of study that enhance the new understanding of a dynamic Moon:

- **Water and OH migration on the Moon.** An exciting development in the past few years was the discovery of water on the Moon, probably of solar wind origin. One focus of our group was to understand how the solar wind interacts with the Moon, how OH and water can be made on the surface, and how these species are transported, destroyed and sequestered in cold traps. A Monte Carlo simulation of water and OH on the surface of the Moon was prepared for the SSLAM special issue in JGR. Figure5.2 shows our model simulation of how OH varies in the lunar regolith as a function of the lunar phase, and as the Moon transits the Earth's magnetotail. In our model the implanted hydrogen can combine with indigenous lunar oxygen to form OH groups. We have modeled many aspects of the solar wind interaction with the regolith and compared the results with the concentrations of OH/H2O deduced from IR spectra. We find that the solar wind source is too low to account for the observations unless ~100 yrs worth of solar wind is allowed to contribute. This timescale is longer than the lifetime of free H2O, longer than the residence time of OH/H2O on the surface, and longer than the diffusion time of implanted material. Using expected lifetimes, the simulations produce concentrations of OH that are 2 orders of magnitude too low to match the observations. Further, the simulations show that the reported diurnal nature of the spectral feature cannot be supported by a solar wind source. The diffusion rate cannot account for the EPOXI observations because they were acquired in the magnetotail. Diffusion also would produce a different latitudinal signal than reported from M3. The diffusion calculations produce a relatively constant value at high latitudes and a larger spread of values at low latitude, in contrast to what is observed. This work, by Hurely et al. (2012) is being submitted to JGR-planets.

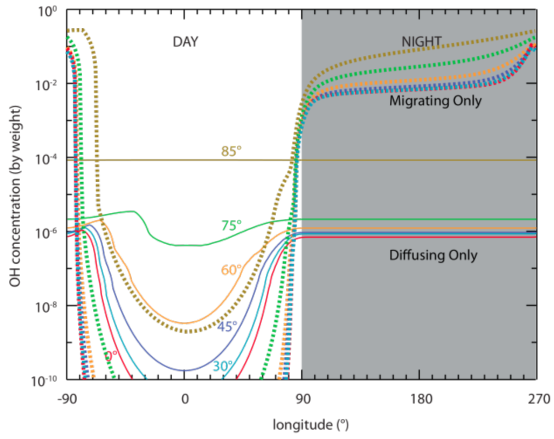

Figure 5.2.2. The solid lines show the concentration of OH in the lunar regolith from implanted solar wind that is diffusing out of regolith grains. The dashed lines show the concentration of OH adsorbed to the surface from water migrating through the lunar exosphere. From Hurley et al 2012

-Other Water/OH studies. Immediately following the 2009 LCROSS and M-cubed lunar water discoveries, the DREAM center began a set of investigations to understand whether the regolith is capable of manufacturing and transporting water. The team started a larger NLSI sub-group focused on the manufacturing of water and the solar wind interaction with the oxygen-rich lunar regolith. This focus group featured key surface interaction members of Ben Bussey's Polar environment team, including Karl Hibbitts and Thom Orlando. The focus group grew organically and continues to meet to understand the role of solar wind protons in altering the solid state matter.

Beside the focus group, DREAM team members performed detailed investigations to constrain the sources of lunar water. Hurley et al [2010] presented (ay LPSC 2010) a focused study on the transport of water and OH assumed to be manufactured by the solar wind. It was assumed that the the peak in the manufacturing occurred at the sub-solar point. Unfortunately, the spatial distribution of water with a minimum at low latitudes did not match this source. At the LPSC in 2011, Farrell et al. [2011] suggested that some of the water that forms the mid-latitude veneer could have been formed by impact vaporization and sputtering from the icy regolith found at the bottom of the permanently shadowed craters. The model is called a 'polar water fountain'. Unfortunately, the water flux from the polar crater sources, when combined, was not large enough to account for the mid-latitude veneer extent and concentration. DREAM team members gave a set of talks at the Wet vs Dry Moon workshop in June 2011, with some of these suggesting that there is a balance between solar wind water losses via sputtering vs solar wind water manufacturing via implantation. Hodge's [2011] GRL paper suggests that nearly all of the incoming solar wind converts to neutral H via surface charge exchange process, and then outgases to form an H corona about the Moon. This view would suggest there is little/no OH manufacturing from solar wind implantation.

- Prediction of full complement of exospheric species and observability by LADEE. 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 a 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)

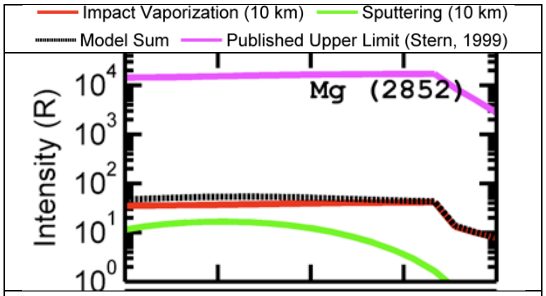

Figure 5.2.3. Our prediction of the intensity of the Mg 2852 Å line at the Moon as a result of several source processes, the published upper limit (purple) and our model sum (dashed black). The analysis is in support of LADEE and presented in Sarentos et al. (2012).

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.

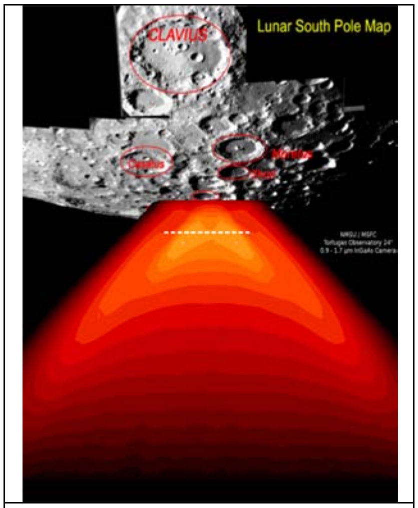

Figure 5.2.4- A model of the LCROSS sodium plume (Killen et al., 2010)

- Study of the volatiles released during the LCROSS impact. When the Lunar Crater Observation and Sensing Satellite smashed into the Moon, members of the DREAM team (Colaprete, Killen, Hurley, Elphic) were watching. The goal of LCROSS was to release ice that might have been sequestered in the extremely cold, permanently shadowed region of Cabeus crater. Indeed, water was released; but it wasn't alone. Another thing that was released by the impact was sodium. Sodium vapor, derived from sodium atoms in lunar minerals, is common in the lunar atmosphere. DREAM team member Killen observed the sodium vapor from the impact using the Stellar Spectrograph at the McMath-Pierce solar telescope on Kitt Peak. DREAM team member Dana Hurley simulated the evolution of the sodium vapor plume assuming different initial conditions with a Monte Carlo model of the Moon's atmosphere. By comparing the observed sodium distribution over time to the modeled distribution, we find which assumed initial conditions best fit the observations. That way we can learn something about the manner in which the sodium was released. We showed that the predicted column density of sodium if the sodium was thrown out isotropically vs. released in the "upside-down lampshade" of crater ejecta. The isotropic case has a much broader cloud close to the surface, whereas the upside-down lampshade has it broadest expanse at higher altitude. Modeling has also shown that the rate at which the cloud expands is highly dependent on the release temperature.

A selection of other key studies and achievements conducted by the DREAM exosphere team, along with the major advancements to the field from those studies, over the first three years of the work period are shown in Table 5.2 below.

Table 5.2 – other key DREAM studies

Title	Leader	Advancement	Deliverable [paper, codes]
Modeling the production of water from solar wind protons	D. Hurley,	Modeling the interaction of the solar wind with the oxygen-rich regolith to create OH and water, and determine subsequent molecule migration	Monte Carlo simulation of water, Paper in SSLAM JGR special issue
Composition and density of the lunar exosphere following a CME	R. Killen	Examine the effects of the enhanced solar wind flux and enhanced fraction of heavy ions in a CME to determine the effect on the lunar exosphere (see also Section 5.4)	Paper in SSLAM JGR special issue
Polar crater water fountain as a source of mid-latitude water veneer	W. Farrell	Examine impact ejecta and sputtering as an energy source in ice-rich polar craters for transporting water to mid-latitudes	Code, LPSC talk

Exospheric composition	M. Sarantos	Predicted the composition of the lunar exospheric metallic species, oxygen and silicon and observability by LADEE.	Paper in Icarus, Exosphere prediction paper for LADEE
Flux estimates of exospheric lunar ions and ion pickup	R. Hartle	Modeling ion production from exospheric neutrals and direct sputtering of ions at the surface and comparison with data	Paper in GRL
Review on space weathering processes	R. Killen	Processes that contribute to space weathering of an exposed planetary body were reviewed	Paper in Rev. Geophys.
Analogs to Mercury	R. Killen	Comparing lunar exosphere to the exosphere of Mercury via MESSENGER, esp. the presence of supra-thermal neutral gas species	Codes, paper in Rev. Geophys.
Study of Lunar H exosphere	R. Hodges	A theory was presented for the lack of an observed H exosphere at the Moon. It is predicted that most of the incoming solar wind protons convert to neutral H to form the exosphere.	Paper in GRL
Lunar exosphere simulation code.	R. Hodges	The Lunar Exosphere Simulator (LExS) toolkit is part of the planning effort for the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission.	Code.
Development of Ion Time of Flight system	Keller, Collier	Instrument development of system to perform ion mass spectrometry	Designs
Sputtering loss of volatiles in polar craters	M. Zimmerman W Farrell	Use analytical and simulation models to determine ion flux & sputtering rates at the surface of polar craters	Code, 3 papers
Vapor release at LCROSS impact	Hurley, Killen	Monte Carlo model of vapor cloud for various species released from LCROSS impact and detected by LRO	Code, Set of papers
Solar Wind Ion control of Na Exosphere	M. Sarantos	Examined a large set of ground-based Na exosphere observations and observed Na intensification in SW	Code, Paper

Summary. The DREAM center was active in one of the most exciting periods in lunar research. Both the LCROSS mission and M-cubed instrument observations will forever change the way we look at the Moon, or any small body. The observation of sequestered water in cold polar regions and the observation of the water/OH veneer at mid-latitudes are truly amazing and suggest water, OH, and organics are more plentiful on rocky bodies than initially envisioned. The DREAM exospheric team immediately incorporated these new ideas into their work, and provided key modeling that constrained the possible source regions of the water. They also provided key observations in support of the LCROSS mission, providing independent confirmation of Na impact vapor mass. These models have extended applications in the understanding of the surface bounded exosphere that may exist at small rocky bodies, and is the topic of future pursuit.

5.3 Advancement in Understanding the Dusty Plasma Environment

Objective Description: During its orbit around the Earth, the Moon encounters supersonic solar wind plasma, energetic particles from solar storms, the near vacuum of the terrestrial magnetotail lobes, and the energetic turbulent plasmas in the terrestrial plasma sheet. This constant and highly variable plasma bombardment, accompanied by solar UV and X-rays, solar energetic particles, micrometeorites, and other perturbing influences, creates a dynamic and active environment around the Moon. These external drivers interact directly with the Moon's surface to create a boundary-layer plasma sheath that surrounds the body, a turbulent plasma wake behind the Moon, and local mini-magnetospheres around small-scale crustal magnetic sources. All of these processes interact with each other and the neutral atmosphere in ways that are not yet fully understood, especially in the polar and terminator regions. **DREAM's second objective is to consider these dusty plasma-surface interactions from a system point of view – from largest to smallest scale.** The breadth of the DREAM investigation ranged from the micro-scale plasma-surface interactions near polar craters, to the newly discovered precursor region extending tens of thousands of km upstream from the lunar surface.

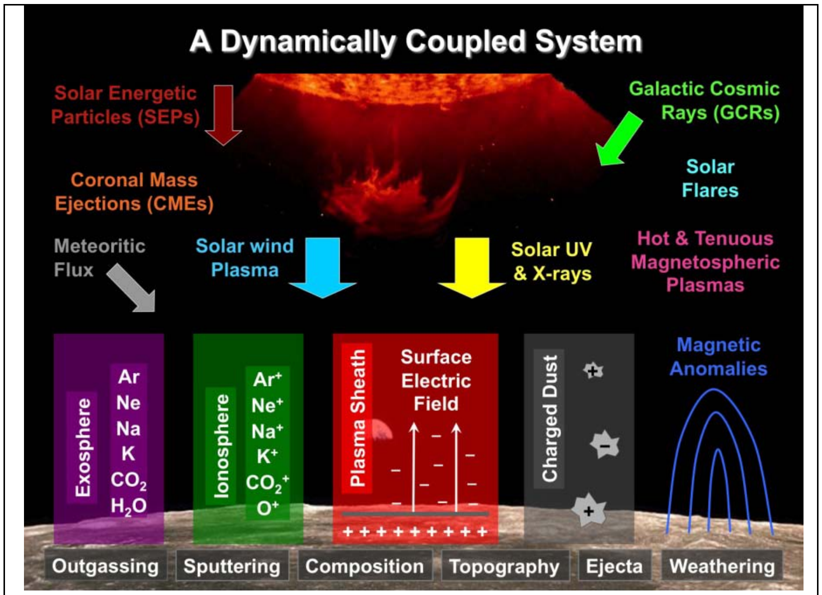

Figure 5.3.1- The dynamic plasma-surface-dust system. DREAM Theme 2 considers how the different aspects of this coupled system interact with each other and respond to external inputs

Relevancy: DREAM's plasma/dust objectives, especially as coupled to the neutral exosphere objectives, are relevant to major cross-cutting themes identified in the latest Planetary Decadal Survey, including #3 (Supply of water and evolution of atmospheres) and #10 (Physical processes that shaped the solar system). DREAM also directly addresses the key science goals identified in the recent NRC report "The Scientific Context for Exploration of the Moon", specifically #4 (Lunar Poles), #7 (Surface Weathering), and especially #8 (Atmosphere and Dust Environment). DREAM addresses physics relevant to plasma-driven space weathering of surfaces and the volatile cycle at the Moon specifically, but also with wide applicability to airless bodies and bodies with tenuous atmospheres throughout the solar system. DREAM, though a data analysis/modeling exercise, emphasized connections to past, present, and future space missions. This investigation was perfectly timed to take advantage of stunning new observations from new lunar missions from China (Chang'E), India (Chandrayaan), Japan (Kaguya), and the U.S. (LRO, ARTEMIS). DREAM developed models and data analysis tools in support of these missions, thereby maximizing the scientific return to the community. DREAM also developed tools and made predictions highly relevant to future lunar missions, including LADEE (Lunar Atmospheric and Dust Environment Explorer).

Previous state of understanding: While numerous missions and theoretical studies have previously addressed the lunar plasma environment, our understanding remained limited until recently. For many years, a simple picture of the Moon as an absorber in the plasma flow held. In this picture, plasma is simply absorbed on the dayside surface, with a wake extending downstream, but no significant effects observed upstream from the Moon. Similarly, our understanding of surface charging and magnetic anomaly interactions remained simplistic, with simple current balance models of surface charging, and simple extrapolations from larger-scale magnetospheres, prevalent. Only in the last few years have measurements of ions and energetic neutral atoms near the Moon with modern instrumentation been made. These measurements have started a sea change in our understanding of the processes that govern the lunar wake, plasma-surface interactions, and plasma-exosphere coupling, with DREAM contributing on all fronts. Meanwhile, our understanding of the dusty component of the lunar environment remains limited, with the few available measurements still mired in controversy, but DREAM models have made intriguing predictions that may be borne out by LADEE.

DREAM Advancements: DREAM brought new theoretical understanding to many aspects of the lunar plasma environment, ranging from lunar surface interactions, to the wake, the polar regions, and the upstream precursor region, using tools ranging from regional and global models to theoretical calculations and data analysis. Key recent advancements from DREAM include the following scientific topics.

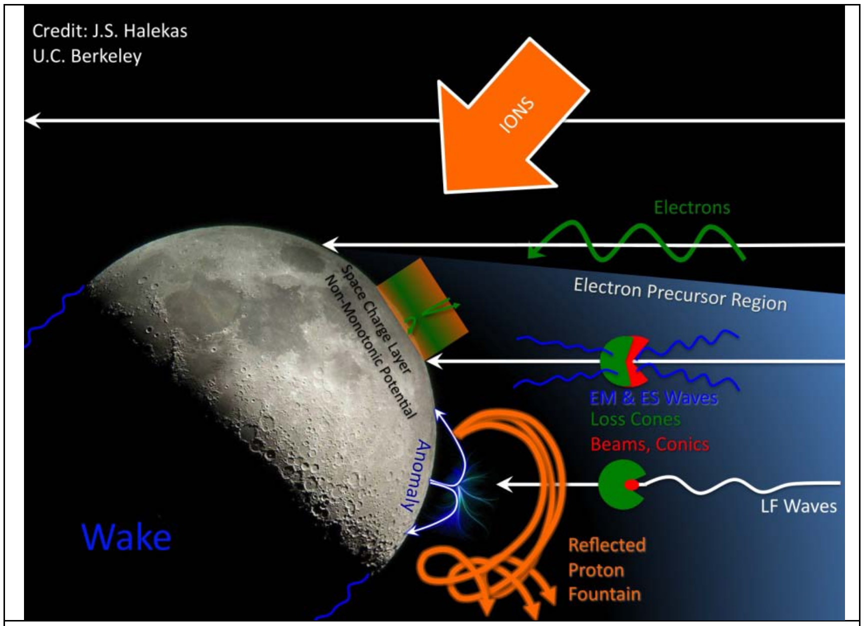

Figure 5.3.2- Lunar Precursor Effects

- **Lunar Precursor Effects**: Utilizing a combination of modeling and analysis of data from Lunar Prospector and from the revolutionary two-probe ARTEMIS mission, DREAM members, led by Jasper Halekas and Andrew Poppe, have now shown the existence of an extended precursor region extending upstream from the dayside lunar surface. This precursor region veritably sizzles with plasma activity, driven by a combination of magnetically and electrostatically reflected electrons, accelerated photo-electrons, and protons reflected from crustal magnetic anomalies [Halekas et al., 2011a, 2011b, 2012; Poppe et al., 2011, 2012]. These free energy sources create significant wave turbulence (both electromagnetic and electrostatic, ranging from ULF frequencies to the plasma frequency) in this region, sufficient to measurably affect the incoming solar wind. **In essence, the solar wind "sees**

the Moon coming" from some distance upstream. In many ways, the region upstream from the Moon is analogous to the Earth's magnetospheric foreshock, despite the fact that it appears there is no shock formed at the Moon.

- **Global Modeling of the Lunar System**: DREAM members, led by Dietmar Krauss-Varban and Pavel Travnicek, have created the most comprehensive global models of the lunar system, including both reflected and sputtered ions for the first time. **Dovetailing with the work above, global models show that lunar-derived ion populations can have significant effects on the passing solar wind.** Even a few years ago, such interactions were not dreamt of. Figure 5.3.3 shows trajectories of low mass sputtered and reflected ions from the Moon. The filamentation of the resulting ion plume (Fig. 5.3.3) represents a fascinating prediction that could be addressed by the ARTEMIS mission.

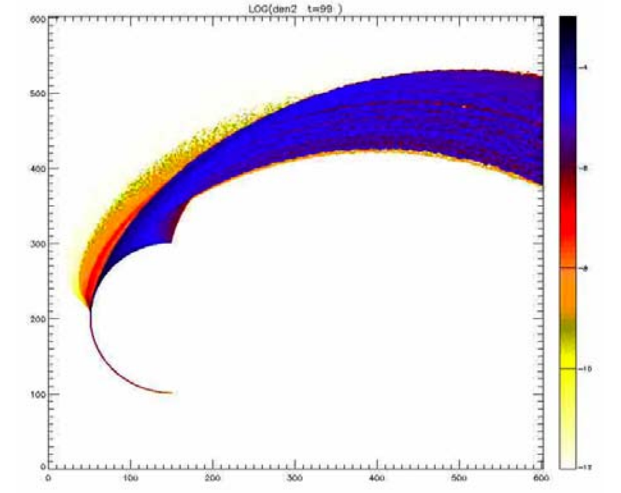

Figure 5.3.3- Trajectories of sputtered and reflected ions from the Moon.

- **Small-Scale Regional Modeling**: DREAM members, led by Bill Farrell and Mike Zimmerman, have created the first detailed models of plasma flow near lunar topographic features such as craters and permanently-shadowed regions (PSRs). These models show that mini-wakes form in these regions, and that electric fields developed as a result of charge-separation between the light electrons and the heavier and slower ions drive ion acceleration into depressions at the poles and/or terminator regions [Zimmerman et al., 2011]. Figure 5.3.4 shows a cartoon of this process (see also section 4 for storm-time results). These deflected ions may in fact contribute significantly to sputtering of volatiles from PSRs, and electric fields may play a role in facilitating dust transport at the poles and/or the terminators. **These regional models consider ground-breaking new physics, that together with the global models detailed above, revolutionizes our understanding of the near-Moon plasma environment and its effects on the surface and dust.**

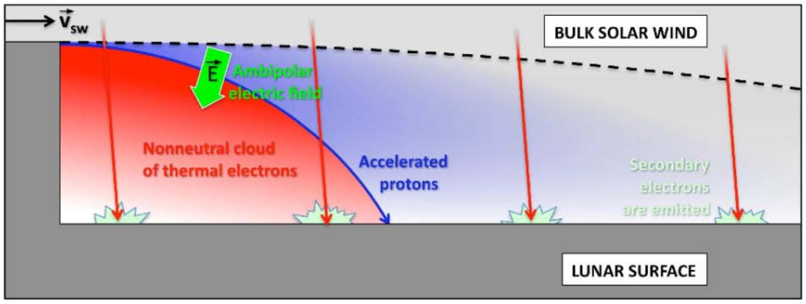

Figure 5.3.4- Mini-wakes formed near polar/terminator topography.

- **LADEE Prediction of High Altitude Lunar Dust.** DREAM investigators Tim Stubbs and Dave Glenar merged a modified McCoy ‘0’ lunar dust model (obtained from Apollo Command Module Camera analysis) with dust light scattering calculations to derive a prediction of the dust light scattering expected to be observed by the LADEE spacecraft in its low altitude orbit. Figure 5.3.4 shows a key result: That the scattered light from dust should dominate over the sodium glow, by a factor of ~10^4. The team also reanalyzed the original Apollo camera observations to determine the range in character of the dust that is consistent with the observed glow [Glenar et al., 2012].

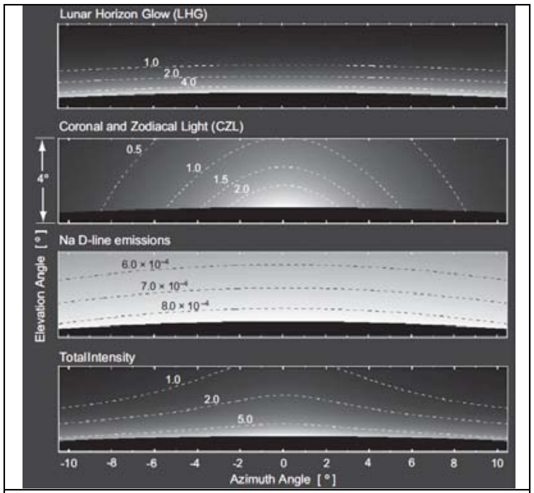

Fig 5.3.4 – Dust light scattering based on the McCoy ‘0’ model and Mie scattering calculations, as compared to sodium (from Stubbs et al., 2010)

A selection of other key studies and achievements conducted by the DREAM plasma/dust team, along with the major advancements to the field from those studies, over the first three years of the work period are shown in Table 5.3 below.

Table 5.3: Other Plasma/Dust Studies			
Title	Leader	Advancement	Deliverable [paper, codes]
Lunar Dust Pendulum	Collier	Demonstrated the swarm-like motion of small dust grains lofted near a shadowed crater	Code, paper in ASR.
Lunar surface charging model using LOLA data	Stubbs	Creating a highly detailed predictive model of surface charging over the entire Moon, as a function of solar illumination conditions	Charging code utilizing LOLA topography
Astronaut charging within polar craters	Jackson	Found that the reduction in plasma flow into craters created excessively long dissipation times	Code, paper in J. Spacecraft and Rockets
Lunar surface charging investigations with LP	Halekas	Understanding the effects of secondary emission on surface charging in the deep wake	JGR and PSS papers
Surface charging modeling and data analysis	Poppe, Halekas	First PIC models of non-monotonic potential distributions and their acceleration of photoelectrons from the surface, and comparison to ARTEMIS observations	Two GRL papers and one JGR paper
Lunar dusty ionosphere modeling	Stubbs	Creating a new model of the lunar ionosphere in which dust-generated photoelectrons play a significant role	GRL paper
Nightside Ionosphere	Farrell	Demonstrated that an He+ exosphere could be formed associated with electron impact ionization	Code, paper in Icarus
Dust levitation and cohesion	Marshall/ Richard	Investigating the role of dust agglomeration in dust charging, surface cohesion, and levitation	PSS papers
Fractal dust model	Collier	Demonstrated that a ‘rough’ dust surface has an unexpectedly large charge capacity	Code, AGU 2011 talk
Ion inflow around Magnetic Swirl regions	Keller	Modeled the inflow of newly-released sputtered ions into magnetic concentrations	Code, LPSC & LSI Forum talks
Wake investigations with ARTEMIS	Halekas	Description of the natural formation of counter-streaming protons, alphas, and electrons in the wake and their effects	SSR Paper

Secondary Radiation Cloud	Spence	Examine the development of a secondary radiation cloud formed from incoming GCRs via LRO's CRaTER measurements	
Deep Dielectric Breakdown	Jordan	Use LRO CRaTER data to infer effect in regolith	LPSC presentation
LADEE Dust Light Scattering Experiments	Marshall	Build system to detect light scattering from submicron dust and test for calibration of LADEE UVS	Lab system, LSI-Forum presentations
Light Scattering from Irregular-shaped lofted dust	Richard	Used Discrete Dipole Approximation and supercomputing facility to examine light scattering from rough shaped exospheric dust	Code, paper in PSS
Photo-emission of LCROSS dust plume	Farrell	Model of impact plume ejecta and electron discharging when in sunlight	Code, LPSC talk, manuscript in prep
Plasma expansion after an impact	Zimmerman	1D and 2D plasma PIC codes of plasma expansion process following an w/ lunar surface	Code
SIDE data Restoration and Analysis	Collier	Working with intern, team is restoring the ALSEP SIDE data and examining ion mass analyzer	Code, 2 papers, Student award

Summary. The objective of the DREAM plasma/dust team was to address the coupled dusty plasma/surface system from the small scale to the large scale, as well as working with other teams to derive the ties between the dusty-plasma and the exosphere. This team has fully succeeded in these objectives. We have created regional and global models of the Moon-plasma system that create a better understanding of the environment, and lead to a number of fascinating predictions that may be borne out by current and future missions such as ARTEMIS and LADEE. We have also created theoretical tools, and participated in analysis of data from a number of missions, similarly expanding our understanding of the lunar environment. The simple picture of an absorbing Moon that hardly affects the ambient plasma is conclusively finished. Instead, we now know that the near-Moon region is turbulent and interactive, with an unexpectedly broad range of plasma processes taking place. We also know that these plasma processes lead to fascinating effects at the surface interface that may have profound effects on the evolution of the surface and the exosphere. These advances will guide us in our understanding of not only the Moon, but the wide range of airless (and nearly-airless) bodies in the solar system.

5.4 Integration and Extreme Events

Objective Description: While DREAM consists of a set of plasma, neutral gas, and surface modelers, the power of the team is brought to bear when modeling efforts are integrated across lines of subject-matter. It is well-known that the plasma-surface-exosphere system of our Moon, Jupiter’s and Saturn’s icy moon, and that of any exposed rocky body are interconnected. The degree of interconnection depends upon the nature of the plasma and surface. For example, the energetic plasmas about the icy moons at Jupiter and Saturn are well-known sputtering sources that create extended exospheres about these bodies. For our own Moon, an underlying question is the degree of connection between the plasma-surface-exosphere systems. **Given solar storms and lunar impacts that dramatically alter environment, we suspect the plasma-surface-exosphere connectivity may reveal itself more fully or on an entirely new way under extreme conditions.** As such, an objective of DREAM is to examine the environmental system during nominal and extreme conditions to discover any hidden connections.

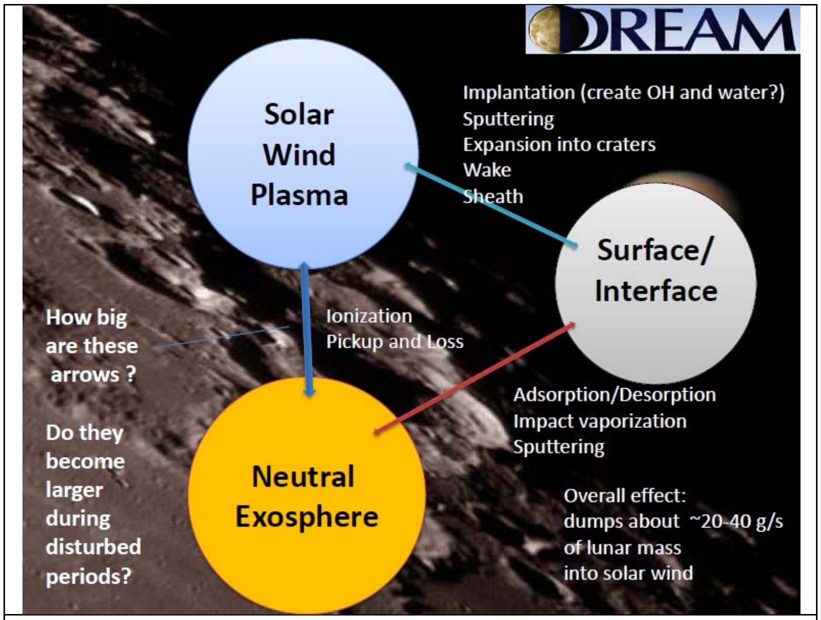

Figure 5.4.1- The connected plasma-surface-exosphere system. Objective 3 considers how these interconnections vary under extreme conditions.

A prime example of such a new connection is the 2009 M^3 IR discovery of an existing water and OH veneer that appears to exist on the lunar dayside. It has been postulated that a source of this veneer is the incident solar wind: energetic protons may convert to OH when implanting within the oxygen-rich SiO_2/FeO_2 lunar surface. Some of this OH and water may leave the surface to move in the exosphere via desorption processes. This scenario is a prime case demonstrating new intriguing connections between the plasma-surface-exosphere systems relating to volatile manufacturing and migration.

Relevancy: The solar wind plasma may be a possible source of key volatiles like OH, when incident with the oxygen-rich regolith. However, solar wind plasma incident at the lunar surface at 1 keV can also be a sputtering source/volatile loss process. At the recent LEAG sponsored Wet vs Dry Moon workshop in June 2011, DREAM team members presented a set of papers addressing this ‘dyslectic’ role of solar wind plasma in volatile manufacturing and maintenance. Given the tight interconnections, this objective ties to NASA’s **Vision and Voyages Decadal report (2011), especially in Cross-Cutting theme #3 (Supply of water to inner planets) and # 10 (Chemical processes shape solar system)** where solar wind plasma is continually interacting with the oxygen-rich lunar regolith. In fact, exposed rocky bodies may be far more hydrated than originally perceived. The objective is also ties to the NAS/Scientific Context for Exploration of the Moon (SCEM2007) in theme # 4 (lunar poles as special environments) , #6 (impact processes), #7 (space weathering) and #8 (atmosphere-dust environment). In this objective, we in fact study the changes in the lunar environment during solar extrema and impacts. Finally, the study of solar storms at the Moon ties to the Heliophysics Science at the Moon (2007) report in Theme # 1 (Plasma interactions and Environment) and Theme # 2 (Weathering and Radiation).

Previous state of understanding prior to DREAM. While it was recognized that the solar driving plasma could influence the lunar exosphere, the investigation into coupling processes has never really been explored in great detail. For example, known reviews on the subject either do not mention or give little detail on the plasma-surface-exosphere coupling that would go on at the Moon. The literature is actually strongest for the icy moons at the outer planets where energetic magnetosphere plasma incident at icy interfaces generate copious amounts of exospheric atoms due to the high sputtering yields from ice.

DREAM advancement. In order to understand the plasma-surface-exosphere coupling at the Moon, we considered the reaction to the Moon to a strong coronal mass ejection (CME) emitted from the Sun. We anticipated that the dynamic system coupling would reveal itself when the space environment became extreme. We thus developed and performed a year-long DREAM science team focused study called SSLAM: Solar Storm/Lunar Atmosphere Modeling that ran from Summer 2010 to Summer 2011, punctuated with DREAM's first Lunar Extreme Workshop (LEW) to present and discuss SLAM results.

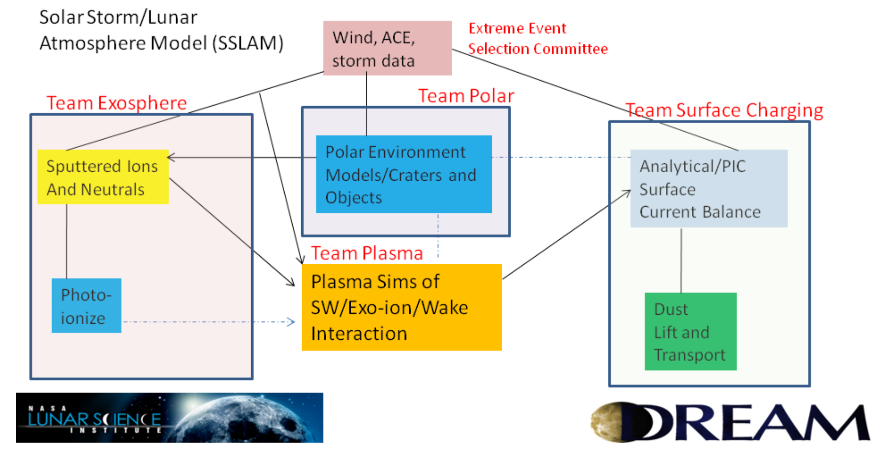

Figure 5.4.2- Block diagram of the Solar Storm/Lunar Atmosphere Modeling (SSLAM) effort.

Figure 5.4.2 shows a block diagram of the cross-integrating SSLAM system. Individual blocks represent separate codes (or sets of interconnected codes); each run on separate platforms and managed by a model curator (usually the model/code developer). The connecting lines show the flow of model data products between the codes. The set of models have a common input (we selected the 1-4 May 1998 storm period) and exchange products in a specific sequence. As a consequence, the synthesized component-level models act quasi-coherently to form an overall system-level model that examines the solar-lunar connection (and specifically a CME passage by the Moon) in a way that has not been done previously. A number of **key advancements were found from the SSLAM study** including:

- The CME mass flux increased dramatically at the exposed lunar surface for the 2-3 May 1998 CME passage. The increase in plasma density and increase concentration of heavy ions will make the incident mass flux at the dayside surface on the order of ~ 10^{-13} kg/m^2-s which over the two day event corresponds to about 300 tons of penetrating light ions onto the dayside lunar surface [Farrell et al., 2012].

- Killen et al. [2011] created a weighted yield appropriate for the CME driver plasma in 2-3 May 1998, and found that CME-sputtering becomes the dominant process in releasing material from the Moon with both volatile and refractory species dayside source rates at levels 20-50 times higher than in the nominal solar wind. Hence species like Si, Fe, and Ti begin to populate the exosphere and escape the Moon. Over the course of the 2-day passage of the CME driver gas, there could be 100-200 tons of mass eroded from the Moon via CME sputtering (for 25% -50% of sputtered atoms escaping lunar gravity). While this loss is surprisingly large, we note that the CME itself also delivers a comparable amount of material to the surface in the form of the driver-gas protons and heavy ions. Figure 5.4.3 shows the enhancement in the sodium exosphere as a result of the enhanced CME sputtering. Note that the density is larger and the scale height of the exosphere changes from ~100 km in solar wind conditions to nearly a full lunar radii during the CME. This work was recently published in JGR-planets and has been highlighted by a recent press release (http://www.nasa.gov/topics/solarsystem/features/dream-cme.html).

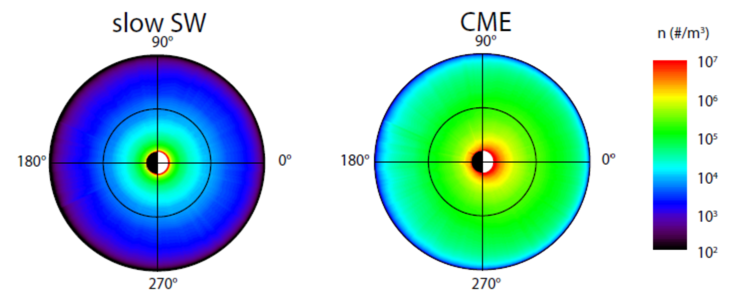

Figure 5.4.3- The enhancement in the sodium exosphere from CME sputtering (from Killen et al. 2012).

- The exospheric team also produced values for the expected CME-driven sputtered ion component and these newly born ions were placed in a 2D and 3D plasma hybrid simulation [Krauss-Varben et al., 2012] to determine their trajectories in a disturbed solar wind conditions. During a CME passage, it was found that there is a great increase in reflection ions and also sputtered ions. Figure 5.4.4 shows the sputtered ions (like Si+, Fe+, and Ti+) get initially accelerated by the solar wind convection electric field, to form a sort of 'fountain' of ions from the dayside surface. While the E-field accelerated the ions outward, the vB magnetic forces then make the ions gyrate and move with the solar wind. This process is call 'pickup' and adds mass to the passing solar wind magnetic field. Validation of such effect is currently being carried out by DREAM investigators who are also co-is on ARTEMIS.

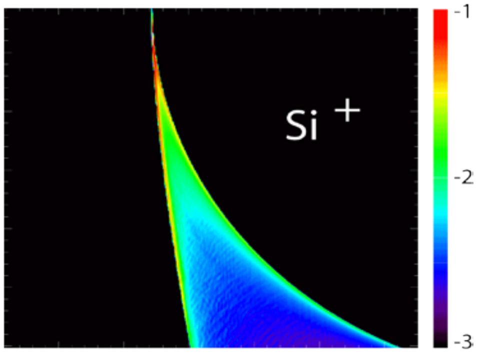

Figure 5.4.4- Sputtered regolith-originating ions get picked up by the local solar wind E-field

- Polar crater regions are special environments that in the past have been considered free of solar wind ions since their flow was thought to pass horizontally over the crater tops. However, DREAM modeling [Zimmerman et al., 2011] finds that ambipolar E –field deflects these ions into the crater and, as such, they represent a potential loss of volatiles via sputtering. DREAM Particle-in-cell plasma simulations confirm that during a CME passage, the influx of these ions to the crater floor become greater in both the warm post-shock and late dense CME plasma at the Moon. Figure 5.4.5 shows results from the ion inflow for nominal solar wind, without and with surface effects. This code was then applied to the CME case and these new CME applications will be published in the SSLAM special issue of JGR-planets.

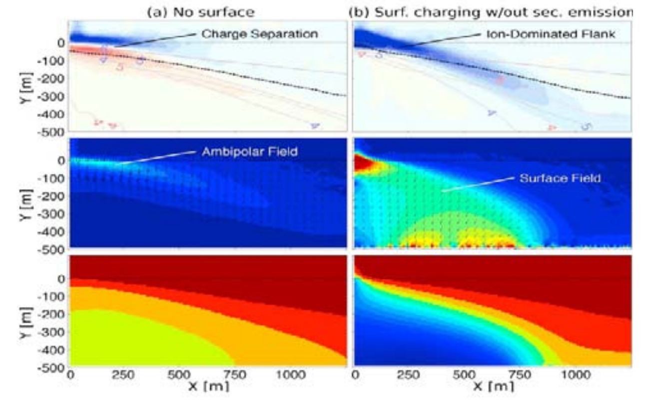

Figure 5.4.5 – Plasma inflow into a polar crater from Zimmerman PIC plasma code [2011].

Other studies incorporated into the SSLAM endeavor are shown in Table 5.4. These studies were presented at the June 2011 DREAM Lunar Extreme Workshop (LEW) and are part of a JGR-planets special issue.

Table 5.4: Other SSLAM Studies			
Title	Leader	Advancement	Deliverable [paper, codes]
Solar Wind Contribution to the Hydroxyl and Water Features on the Lunar Surface	D. Hurley, APL	Modeling the interaction of the solar wind with the oxygen-rich regolith to create OH and water, and determine subsequent molecule migration	Monte Carlo simulation of water, Paper in SSLAM JGR special issue
Surface Charging during CME	T. Stubbs, UMBC	Examine surface charging at equator and terminator with changing conditions of solar storm	New Code, Paper in SSLAM JGR special issue
Object charging in polar craters during CME	T. Jackson, GSFC	Using ion and electron flux from Zimmerman code as input, determine the charging and dissipation properties for a roving astronaut in the low plasma flux crater environment. Strong ties to Exploration.	Code, results part of Zimmerman et al. 2012 SSLAM paper
Trapping of Photoelectrons in the Plasma Sheath	W. Farrell, GSFC	Examining the photoelectron sheath trapping by the surface potential during the passage of a CME. Trapping efficiency found to change with CME flux	1D PIC code featured in SSLAM JGR special issue paper

Summary. A key element of the DREAM objectives is to integrate the separate exosphere-dust-plasma-surface models to obtain a system level environmental picture of the effect of a solar storm at the Moon. The endeavor took over two years to formulate and come to fruition, but the results of the SSLAM system were intrinsically new and unique, suggesting that sputtering by the CME plasma should create an enhanced exosphere with the release of regolith-type surface atoms. The prediction feeds forward to LADEE which will be flying in 2013, near solar maximum when a CME can pass by the Moon. In yr 4 of DREAM, we anticipate another lunar extreme modeling effort involving the environmental effects expected from a moderate size impact at the lunar surface. Such an impact represents an extreme event that again couples plasmas, neutrals, and regolith released from the impact site. Preparations for this upcoming Lunar Extreme Workshop are ongoing. These type of system-level modeling efforts could only be performed under the umbrella of a larger institution, where both funding and longevity for the coherent effort are consistently available.

5.5 Mission Applications of DREAM Environmental Studies

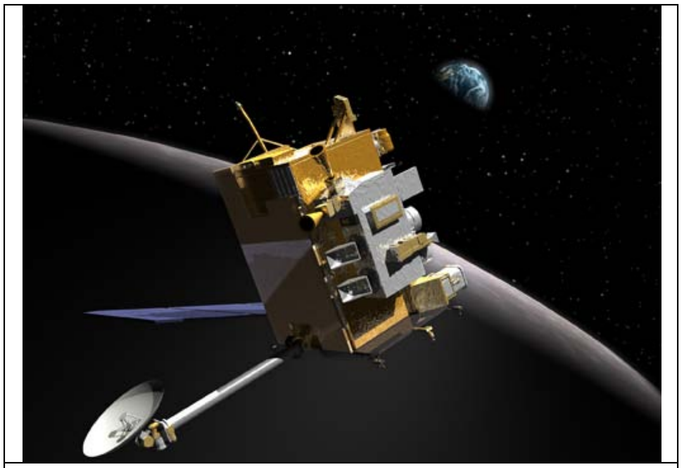

Figure 5.5.1 – Illustration of LRO in orbit at the Moon

Objectives. While DREAM is becoming a renowned center for lunar environmental theory, modeling, & data validation, the DREAM efforts do not stand in isolation. Their intrinsic value to NASA lies in their strong support of ongoing and exciting missions in both SMD and HEOMD. This section summarizes this support over the three year DREAM investigations.

Relevancy. Missions like LRO, LCROSS, and LADEE are already justified under past & current Decadal studies, NRC's Scientific Context for Exploration of the Moon (SCEM), and the evolving needs of the lunar exploration community. Together these missions total an investment of ~$1B in terms of hardware and infrastructure. By supporting these missions, DREAM is by definition also supporting the highest level objectives of both SMD and HEOMD.

Previous state of understanding prior to DREAM. While mission observations provide primary new advances, the DREAM center supports and enhances these finding by providing additional observations (e.g., Killen's LCROSS ground based studies, see Section 5.2), noteworthy modeling analysis (e.g., Poppe and Halekas simulations of the ARTEMIS precursor region, see Section 5.3), and critical predicative analysis to help frame expectations (e.g., Sarantos LADEE exosphere , see Section 5.2, and Stubb & Glenar LADEE dust predictions, see Section 5.3). While these missions would certainly have proceeded in the absence of DREAM, with the addition of DREAM center activities these missions have obtained support that will enhance the probability that their observations will lead to new discoveries.

DREAM Advances to the Objective: DREAM team members continue to have deep involvement in recent and planned lunar missions, and have simultaneously 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 – enabling a seamless interface to the resources available within the DREAM group.

A. Mission Support

Table 5-1: Participation in lunar missions by DREAM team members

	Mission
A. Colaprete	LCROSS PI, LADEE UVS PI
G. Delory	LADEE Deputy Project Scientist; ARTEMIS Co-I
R. Elphic	LADEE Project Scientist; LRO Diviner Participating Scientist
W. Farrell	LADEE SDT Co-lead; ARTEMIS Co-I
J. Halekas	ARTEMIS Deputy PI; Kaguya Collaborator; LP data analysis
R. Hodges	LADEE NMS Co-I
D. Hurley	LRO LAMP Co-I

J. Keller	LRO Deputy Project Scientist
A. Poppe	LP data analysis
T. Stubbs	LRO Participating Scientist; Dawn at Vesta data analysis
R. Vondrak	LRO Project Scientist

DREAM has collaborating mission footprints in nearly all recent and current lunar missions as shown in Table 5-1. 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 R. Elphic, 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. Team member R. Elphic is a Participating Scientist on the DIVINER instrument team. An emerging area of DREAM-LRO collaboration involves the use of DREAM-derived lunar surface potential maps to assist LRO team members in the hunt for Lunar Horizon Glow using LAMP, LROC, and other instruments.

LCROSS: DREAM team members Rosemary Killen and Dana Hurley continue their modeling of the LCROSS sodium plume, with a set of papers published. Also, DREAM dusty-plasma investigators W. Farrell and T. Stubbs have developed an LCROSS analog particulate discharging model (Fig 5.5.2) that features the electrical interaction of the plume ejecta material with the photo-electron rich environment during its trajectory. This ejecta plume modeling was presented at the LPSC 2011 meeting.

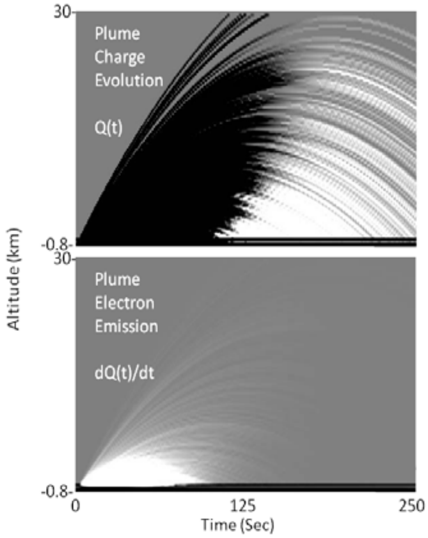

Figure 5.5.2- A model the grain charge evolution in an LCROSS-like impact plume (Farrell et al., 2011). In top panel, dark regions are (-) charged grains and white regions are (+) charged. In bottom panel, white region has large dQ/dt.

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; a key Kaguya Co-I, M. N. Nishino, is visiting UCB-SSL in late February/early March 2012 for several weeks to continue this collaboration through in-person exchange of ideas and data analysis. Co-I Elphic is also a member of the PACE science team for the ion mass spectrometer component.

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. These team members have contributed to science planning for lunar encounters and nominal operations in lunar orbit. 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.

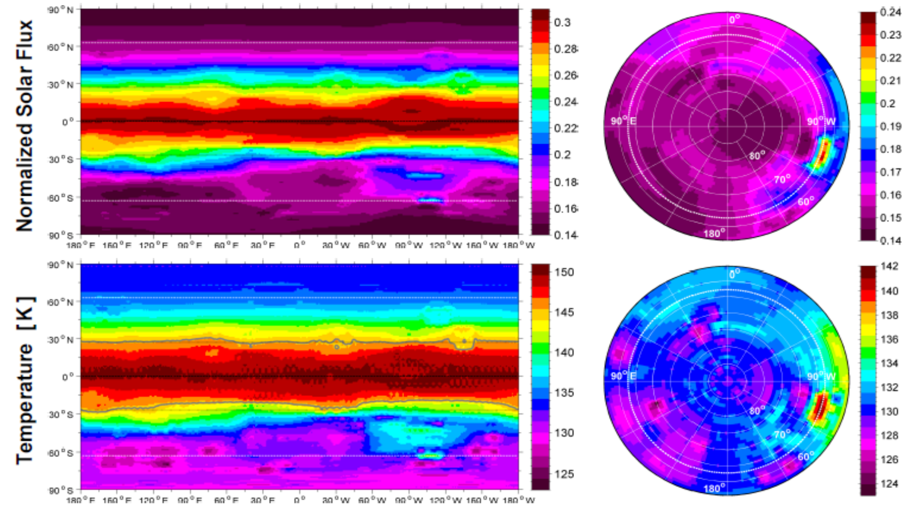

Figure 5.5.3-A model of the Vesta sun and thermal environments

DAWN at Vesta. DREAM center's Tim Stubbs recently examined the thermal and sunlight environment at Vesta (Figure 5.5.3) and determined that the rocky body could harbor volatiles in its near-surface. In essence, this work extends the models that were developed for the Moon to a small body, and illustrates how DREAM tools can be applied to other objects.

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. The DREAM center interacted and supported 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 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 is supporting a Czech proposal in a formulation study for a dusty plasma package on a lunar lander that is under consideration by ESA. Lunar Dust Environment and Plasma Package (L-DEPP) will be designed to study the dynamics of the dusty-plasma sheath of the near-lunar surface with exploration applications in mind. In this case, the European group recognized the two NLSI teams as US leaders in this field, and as a combined team created an international group to support the development of this package. The opportunity is a great example of NLSI's extension well beyond domestic borders and into the international arena.

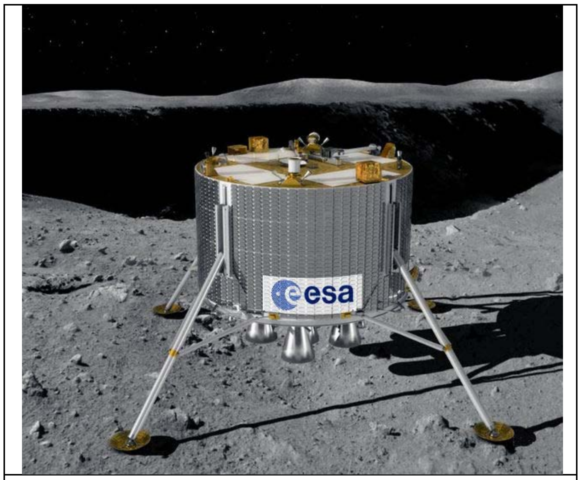

Figure 5.5.4 – ESA's lunar lander concept

Suborbital Dust Experiments. Greg Delory and John Marshall have developed a dust experiment designed for the micro-gravity environments provided by parabolic aircraft and the emerging series of commercial reusable suborbital vehicles. The experiments relate to fundamental physical processes affecting dust dispersion and aggregation, including lunar-relevant parameters, 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 and is leading to an dedicated ISSI lunar study proposal.

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. The DREAM lunar environment center 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. Unfortunately, due to current budgetary instability in both SMD and HEOMD, the pursuit of the line was suspended. However, the DREAM center 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.

5.6 DREAM interconnection to other NLSI Teams

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 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.

This summer, DREAM will also welcome Jason McClain from Thom Orlando's Georgia Tech (funded under Bussey's Polar Environment team) as a new DREAM post-doc working with Dr. John Keller at GSFC. They will perform lab studies of the effect of solar wind ions incident with lunar regolith. Jason made this cross-team connection via the DREAM/SEPLP water focus group.

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 a number of joint papers and in the last year Dr. Poppe has moved onto DREAM as a post-doc at Berkeley. 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 DREAM models. DREAM team members strongly encouraged & supported the recent CCLDS-sponsored LDAP Jan 2010 meeting which cemented a strong bond between groups.

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 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. 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 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:

-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.

5.7 DREAM Education and Public Outreach

Objective. DREAM lunar modeling and data activities are not just of scientific relevance. They are in fact exciting and can be used as learning tools for students of all ages. DREAM's education and public outreach (E/PO) team ensures that the science team's models and messages get properly transferred to students and the general public. The DREAM E/PO team does this in unison with other NLSI E/PO teams guided under the effort of NLSI.

Relevancy. The DREAM E/PO effort is consistent with NASA's current Education Strategic Coordination Framework, specifically Outcome 2, which seeks to attract and retain students in STEM disciplines through a progression of educational opportunities for students, teachers and faculty. Through the Lunar Extreme Program and Workshops, DREAM satisfies the following objectives:

Objective 2.2 – Provide long-duration and/or sustained professional development training opportunities to educators that result in deeper content understanding and/or competence and confidence in teaching STEM disciplines.

Objective 2.3 – Provide curricular support resources that use NASA themes and content to a) enhance student skills and proficiency in STEM disciplines; b) inform students about STEM career opportunities; and c) communicate information about NASA's mission activities.

Objective 2.4 – Provide K-12 students with authentic first-hand opportunities to participate in NASA mission activities, thus inspiring interest in STEM disciplines and careers, as well as provide opportunities for family involvement in K-12 student learning in STEM areas.

DREAM E/PO Advances. There are three primary areas the DREAM E/PO team has made significant contributions: formal education, outreach, and supporting NLSI's lunar E/PO community initiatives. We detail these below.

A. Formal Education:

Lunar Extreme Program

DREAM's formal education program is focused on student and teacher participation with scientists. The primary component of the program is two Lunar Extreme Workshops (LEWs) and the supporting materials developed for each LEW. The first LEW was held at Goddard Space Flight Center (GSFC) in 2011. It brought together scientists and modelers from the DREAM team with advanced students and their teachers from two high schools. The LEWs allowed student and teacher participants to interact directly with scientists and to experience the process of science in action. Participation in the LEW and pre-LEW training exposed students to science, technology, engineering, and math (STEM) careers and engaged 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 syllabus 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 syllabus for the first LEW. We also worked with an external evaluator to develop our evaluation plan and tools, such as student and teacher surveys. In addition, we worked with a Web designer to design and build the DREAM E/PO Website (http://ssed.gsfc.nasa.gov/dream/DREAM/), which served as the primary source of information for recruitment purposes and the provision of the syllabus to participating students. 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 launched in January 2011. During the Program, students independently read and reviewed the resources in the syllabus on their own at home. Their progress and understanding was checked during discussions with their larger student/teacher team during regular meetings once a week for sixteen weeks. During the meetings, students received instruction and participated in hands-on activities. They also participated in Webinars with DREAM E/PO and science team members. The Webinars provided the opportunity for students to virtually "meet" science team members before interacting with them in person at the LEW. The Webinars also gave DREAM team members an opportunity to provide context for the syllabus topics within the DREAM framework while also introducing students to STEM careers.

Webinars were graciously provided by Dr. Sarah Noble (GSFC), Dr. Tim Stubbs (UMBC), Dr. Jasper Halekas (UCB), Dr. Nicholas Gross (BU) and Dr. Telana Jackson (GSFC).

In program year three, the 2011 Lunar Extreme Program culminated with the student/teacher teams traveling to GSFC in June to participate with DREAM scientists in a LEW focused on the effects of solar storms on the lunar surface. In addition to hearing from and interacting with DREAM scientists during the LEW, students and teachers also presented their observations of the May 1998 solar storm data being used by the DREAM team in their models, solved problems on ion landing locations and sputtering rates in polar craters and presented results to LEW attendees, toured GSFC, met non-DREAM scientists while touring science exhibits during the annual "Science Jamboree", interacted with engineers working on technologies related to DREAM science to learn about communication between scientists and engineers, and heard from an undergraduate intern coordinator about NASA's intern programs and how to apply. According to feedback received from the students about their experiences in the Lunar Extreme Program and Workshop, they most liked getting to interact with the scientists and observing how the scientists interacted with each other. Overall, they found the Program and LEW valuable because it gave them an opportunity to see how science is done and what it's like to be a scientist. They also left the program and LEW with a different view of the Moon (as more dynamic) than before. The remainder of program year three consisted of refining the syllabus for the second LEW to incorporate both new content, focused on lunar impacts at various scales, and feedback received from participants in the first LEW. We also began recruiting participants for the 2012 Lunar Extreme Program and LEW, which will take place in November.

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 provide the public with a perspective of the Moon and lunar science with which they may not be familiar. Although the number of participants at individual 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:

- April, 2009: Jasper Halekas gave a public lecture for 60 attendees at the SETI Institute.
- April, 2009: Dave Glenar gave a lecture to 20 adults and 20 high-school students at a Rotary Club in Dundee, NY.
- September, 2009: Rosemary Killen gave three talks on exopsheres for a total of 250 people at the University of Maryland Observatory's Open House.
- November, 2009: Rosemary Killen gave a lecture to 75 retirees at the Goddard Recreation Center.
- November, 2009: Rosemary Killen gave a seminar to 12 graduate students and six faculty members at Catholic University.
- November, 2009: Tim Stubbs gave a talk and tour to 20 4-5 year olds from Rainbow Pre-school at the Goddard Visitor Center.
- December, 2009: Dana Hurley gave a presentation to 25 students ages 7-8 at Pointers Run Elementary School in Clarksville, MD.
- 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.
- March 2011 – Dick Hodges gave a talk on the lunar atmosphere to approximately 50 graduate students and faculty members of the Laboratory for Atmospheric and Space Physics at the University of Colorado.
- May 2011- Rosemary Killen gave a set of talks at St. Alban's school in Washington DC
- July 2011- Rosemary Killen gave the guest talk to the Lunar Planetary Space Academy High School students at the Univ. of Maryland.
- October 2011 – Dick Hodges gave a talk on space exploration to approximately 50 fourth grade students and teachers at Breckenridge Elementary School in Breckenridge, CO.

Large Public Outreach Events

Another avenue by which DREAM shares its research with students and the general public is through 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 a two-way conversation about the Moon and current lunar research.

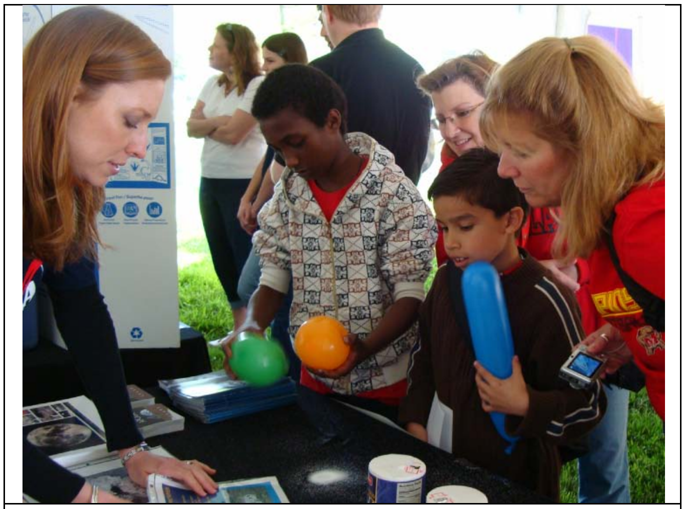

Figure 5.7.1 – DREAM at Maryland Day 2011

Maryland Day

DREAM has hosted a hands-on exhibit at "Maryland Day" at the University of Maryland, College Park in each program year (April 2010, 2011, and 2012) thus far. Approximately seventy-five to one hundred thousand members of the public, representing a range of age groups, attend Maryland Day. At these events, DREAM team members have 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 represents 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 a monitor with data visualizations, and handed out NLSI brochures, stickers, and Moon lithos.

International Observe the Moon Night

International Observe the Moon Night (InOMN) is another primary outreach event participated in by DREAM team members. DREAM has participated in both the inaugural and subsequent InOMN events on September 18, 2010 and October 8, 2011, respectively at the NASA Goddard Visitor Center. Approximately 500 members of the public, representing a range of age groups, were in attendance both years. DREAM team members contributed to Goddard's InOMN events in a number of ways. Several scientists volunteered at the "Chat with a Scientist" table both years, where they engaged the public in conversations about the Moon, DREAM's science goals, other scientific interests, and their career paths. Other scientists have created visuals for use at various exhibits and have given public lectures to InOMN participants. DREAM E/PO team members contributed to planning and implementing the Goddard InOMN event and the coordination of the greater worldwide InOMN effort.

C. Supporting NLSI's Lunar E/PO Community Initiatives:

DREAM E/PO team members have contributed to, and provided feedback on, NLSI-wide E/PO initiatives. One initiative is the development of a new Moon-focused Website on the NASA portal (moon.nasa.gov). The Website, once launched, will be a central location for the public to get information on NASA's lunar missions and research, as well as ways that they can participate via citizen science initiatives, events, etc. The second initiative that E/PO team members contributed to is the development of a new Lunar Science Education Vision. The Vision describes the contributions that lunar science and education efforts can make to our nation's overall quality of STEM education. It includes strategies and recommendations representing areas of particular need or particular strengths that should receive continued support.

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5.9 DREAM Conference Papers, LPSC and Proceedings

Total Conference Papers/Presentations, Extended abstracts, Poster presentations and Oral presentations: 131
These are listed at: http://ssed.gsfc.nasa.gov/dream/papers.html

LPSC Abstract (student and post-doc as lead author are underlined):

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.

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., 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.

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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.

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Hurley, D. “Surficial OH/H2O on the Moon: Modeling Delivery, Redistribution, and Loss,” Lunar and Planetary Science Conference, #1844, The Woodlands, TX, March 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. Farrell1 T. J. Stubbs, CHARGING AND SUBSEQUENT DISSIPATION OF A ROVER WHEEL IN THE LUNAR POLAR REGIONS, 42nd Lunar Planetary Sci Conf, Woodlands Tx, 2011.

Jackson T. L., W. M. Farrell, J. E. Bleacher, xPED: THE EXPLORATION PORTABLE ELECTROSTATIC DETECTOR, 43rd Lunar Planetary Sci Conf, Woodlands Tx, 2012.

Jordan, A. P. , T.J. Stubbs, C. Zeitlin, H.E. Spence, N.A. Schwadron, M.I. Zimmerman, W.M. Farrell, ON THE INTERACTION BETWEEN HIGHLY ENERGETIC CHARGED PARTICLES AND THE LUNAR REGOLITH, 43rd Lunar Planetary Sci Conf, Woodlands Tx, 2012.
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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, The Woodlands, Texas. LPI Contribution No.2704, March 1-5, 2010.

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.

Samad, R. L., A. R. Poppe, J. S. Halekas, G. T. Delory, V. Angelopoulos, and W. M. Farrell, Direct observations of lunar pickup ions in the magnetosphere tail-lobes by ARTEMIS, 43rd Lunar Planetary Sci Conf, Woodlands Tx, 2012.

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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., 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.

Zimmerman, M.I., W.M. Farrell, T.J. Stubbs, J.S. Halekas, The plasma wake downstream of lunar topographic obstacles: Preliminary results from 2d particle simulations, 42nd Lunar and Planetary Science Conference, p. 1836, 2011.

Zimmerman, M.I., W. M. Farrell, and T. J. Stubbs, CHARACTERIZING ELECTRON OSCILLATIONS IN A COLLISIONLESS, EXPANDING IMPACT PLASMA, 43rd Lunar Planetary Sci Conf, Woodlands Tx, 2012.

Other Noteworthy Conference Proceedings:

A student proceeding:
Krzykowski, M., M. Collier, and H. K. Hills (2010), Identifying and characterizing VxB events on the lunar surface from the Suprethermal Ion Detector Experiment (SIDE) that was part of the Apollo 14 mission, 62nd International Astronautical Congress, Cape Town, IAC-11-A5.1.7.

Early Career proceeding:
Jackson, T. L. and W. M. Farrell, The Exploration Portable Electrostatic Detector (xPED), 2nd NSBE Aerospace Systems Conference, 2012.

5.10 DREAM’s Early Career Team Members

High School Students in DREAM/Lunar Extreme Program
Adnan Choudhary (Eleanor Roosevelt HS)
Ankush Gola (Eleanor Roosevelt HS)
Michael Lucchi (Eleanor Roosevelt HS)
Sadia Naseem (Eleanor Roosevelt HS)
John Trinh (Eleanor Roosevelt HS)
Yau-Jong Twu (Eleanor Roosevelt HS – Supervising Teacher)
Sarah Baer (Seton Keough HS)
Sara Caton (Seton Keough HS)
Emily Montoya (Seton Keough HS)
Rebecca Stevick (Seton Keough HS)
Jessica Sweitzer (Seton Keough HS)
William Mason (Seton Keough HS- Supervising Teacher)

GSFC’s Lunar Planetary Space Academy Interns
Mindy Krzykowski (U of Alaska, Fairbanks) - intern for two summers (2010, 2011) with Mike Collier.
Justin Wilde (U Wyoming) - intern in 2010 with T. Stubbs.
Emily Kopp (U. Wisconsin/U Az) - intern with R. Killen in 2010.
Maggie McAdams (Mt Holyoke College/UMD)*, Andrea Balbus (CUNY/U.Oregon) and Mikhail Nikiforov (UMD) were in a team led by Paul Lowman in 2009 to study lunar water and He-3 detection.
Matthew Gialich (Cal Poly St) - intern in 2011 with T. Stubbs.
Jacob Wolf (Dartmouth) - intern in 2011 with M. Zimmerman.
Fred Moxley, III (La Tech U.) –intern with Rosemary Killen, 2011
Andrew Ryan (Slippery Rock U/AZ St) - LPSA Assistant in 2011.

**- Ms. McAdams graduated and worked at GSFC as a LPSA deputy for the summer of 2010. She then moved to APL to support lab efforts under Ben Bussey’s NLSI team.*

Graduate Students

Jinni Meehan (Hampton U.)
Nicole Pothier (Hampton U.)
Duminda Kankanmange (Hampton U.)
Heidi Fuqua (UCB)

GSFC Co-op Students
Telana Jackson **

*** Transitioned to CS Temp position in 2009*

Post-Doctorial Team Members

Michael Zimmerman (NRC @ GSFC)
Andrew Poppe (UCB)-Originally Horanyi's CCLDAS grad student who transitioned to DREAM.
Jason McClain (NRC@GSFC) - Originally Bussey's Polar Environment team member advised by Thom Orlando at GaTech, who will now transition to DREAM this summer.
Andrew Jordan (UNH)