NASA Lunar Science Institute

Colorado Center for Lunar Dust and Atmospheric Studies

Annual Report for Year 2

4/15/2010 – 4/14/2011

Table of Contents

1. Summary

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

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

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

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

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

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

2. Lunar Environment and Impact Laboratory (LEIL)

2.1 Overview

A major part of the CCLDAS experimental program is the development of a 3 MV dust accelerator at the new Lunar Environment and Impact Laboratory (LEIL). The objective of the LEIL facility is to accelerate micron-sized grains, which will provide a unique research tool to generate high-velocity dust impacts, closely reproducing the effects of micrometeoroid impacts onto the lunar surface. The LEIL facility, including the accelerator itself and the accompanying target chambers, will be capable of simulating the lunar surface environment, including variable plasma conditions, solar wind, UV radiation, and dust impacts (**Figure 1**).

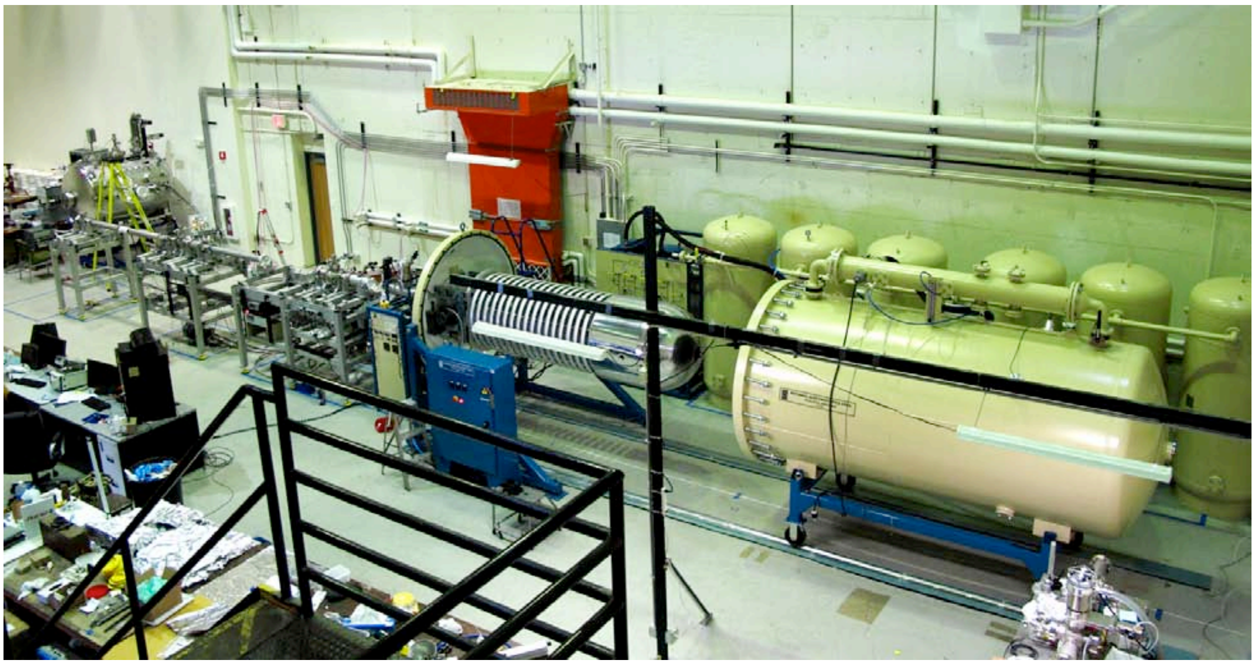


Figure 1. 3 MV dust accelerator installed at in the CCLDAS Lunar Environment and Impact Laboratory. The accelerator is used to simulate the effects of dust impacts with speeds >> 10 km/s for micron sized projectiles. The facility will be also used to test and calibrate plasma and dust instruments, including the Lunar Dust EXperiment (LDEX) for the LADEE mission. The facility is now operational and available for the lunar community for impact studies.

2.2 Site preparation

The LEIL facility is housed in the high-bay of the University of Colorado Nuclear Physics Laboratory, which previously housed a cyclotron accelerator. During this year we have completed the transformation of this space into a working accelerator facility, complete with two working dust accelerators: one 3 MV main beam and a smaller, 20 kV accelerator for component testing. This has included site modifications (power, water, air, etc.) as well as the installation of the Pelletron high-voltage generator, and the complete beam line. Beyond the high-bay experimental hall, we have also occupied a suite of offices, a "sample preparation lab" as well as a meeting room equipped with a videoconferencing system for remote meeting participation.

2.3 Accelerator components

A dust source (**Figure 2**) mounted inside the Pelletron injects highly charged dust particles for acceleration. After exiting the high-voltage (HV) stage, the particle transits through an electrostatic focusing lens, and then through a set of pick-up detectors for the initial determination of the charge, mass and velocity. A particle selection unit utilizes a set of HV deflection plates to reject particles outside the desired mass and velocity range from entering the experimental chamber. A final pick-up detector (**Figure 3**) confirms the particle's arrival.

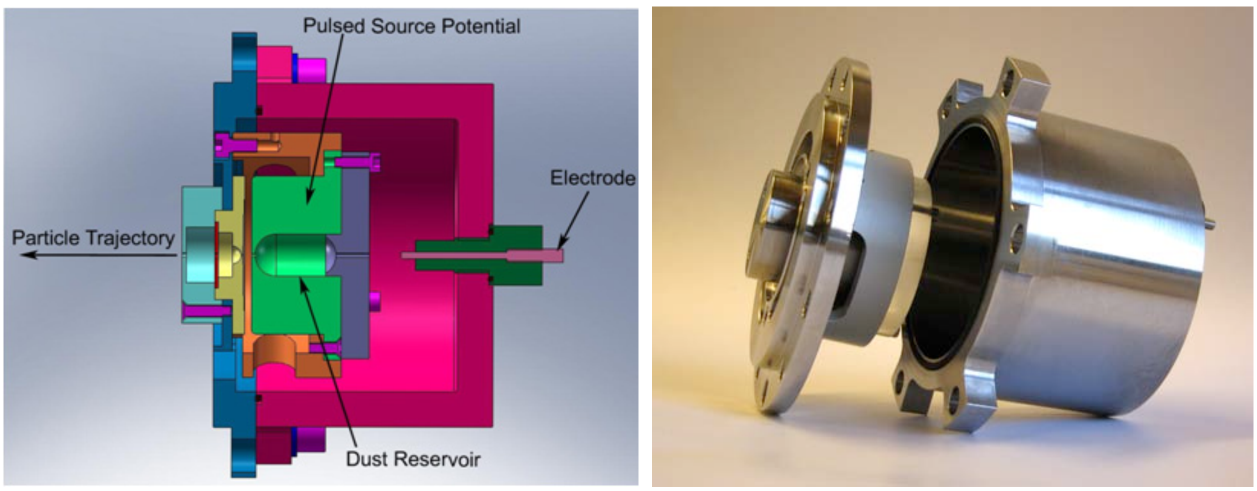


Figure 2. The design of the dust source that enables the injection of highly charged dust particles for acceleration (*left*) with photo of the working dust source (*right*).

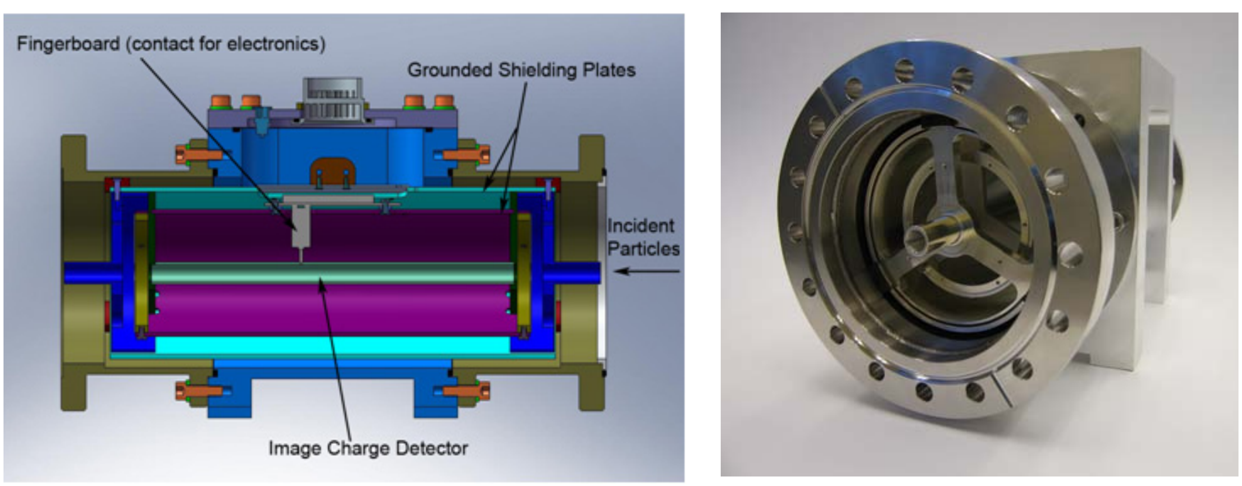


Figure 3. The design of an 'in-line' dust detector to measure the charge and the velocity of a dust particle (*left*) with a photo of a working detector (*right*), for in-flight selection of a desired dust mass and velocity.

Two interchangeable dust sources have been fabricated and tested, with one now installed in the Pelletron. A total of five detectors have been fabricated, the last of which are currently undergoing final calibration. Four of these will be used on the main Pelletron beam, and one on the small 20 kV accelerator.

All other critical components to the accelerator are now fabricated, tested, and in place. This includes the electrostatic focusing lens (Einzel-type) for focusing the beam, and the first version of the particle selection unit (PSU). The PSU is composed of a series of fast logic units and pulse-stretching circuits, enabling the user to select specific particle characteristics in flight for admission to the target chamber. Additionally, we are already well into the development of a "second generation" PSU, based on FPGA technology. For this we are implementing fast filtering of the weakest signals to enable extremely low charge levels to be selected with the PSU. The dust head is driven with an adjustable high-voltage pulser circuit, and all components at the 3 MV accelerator terminal are driven via fiber-optic communication links.

After the mid-January 2011 delivery of the Pelletron unit, bringing the full facility on line progressed quickly, as all of the subcomponents were previously tested and calibrated on the 20 kV "mini-accelerator" (**Figure 4**). This fully functional (though 150x lower voltage) dust accelerator has been invaluable for integrated component testing, and will continue to be used for dust-source preparation and to check out any new components for the 3 MV accelerator.

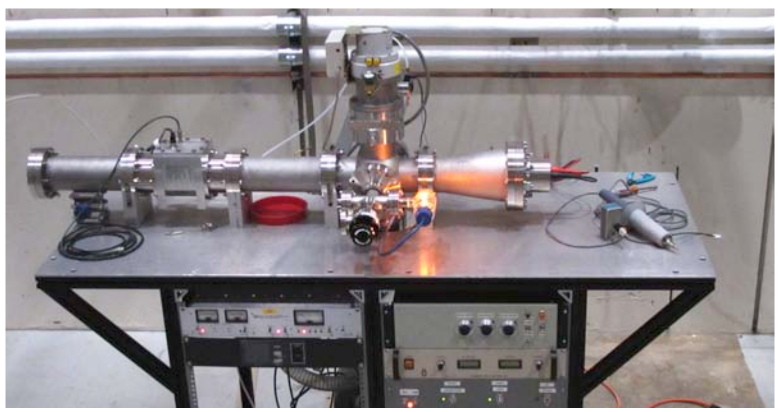


Figure 4. 20 kV "mini-accelerator" for use in component testing and dust-source preparation.

2.4 Primary Impact Chamber

The LEIL will make use of a vacuum chamber 48 inches in diameter and 60 inches long that will house a tray of lunar simulant and an array of diagnostic tools (**Figure 5**). The simulant will be illuminated by 12 excimer UV lamps emitting at 170 nm to create the photoelectron sheath that is created on the Moon by solar illumination. The facility will recreate to the extent possible the lunar plasma environment to investigate dust levitation, transport, and adhesion. Manipulators will be used to find how robotic activity disperses dust and how the mobilized dust adheres to various surfaces. The chamber will also serve as a target chamber for the dust accelerator facility.

2.5 Ultra-High Vacuum Impact Chamber

The LEIL will also make use of a second, smaller vacuum chamber for sensitive detection of impact products, e.g. ejecta, gas, plasma, etc. (**Figure 5**). This chamber will be housed on a movable stand, so that it can be inserted or removed from the main beam line upstream from the large chamber. The small chamber will be differentially pumped (with respect to the beamline) to achieve UHV conditions, necessary for the expected levels of impact products. The UHV chamber is currently being fabricated, with expected delivery in April 2011.

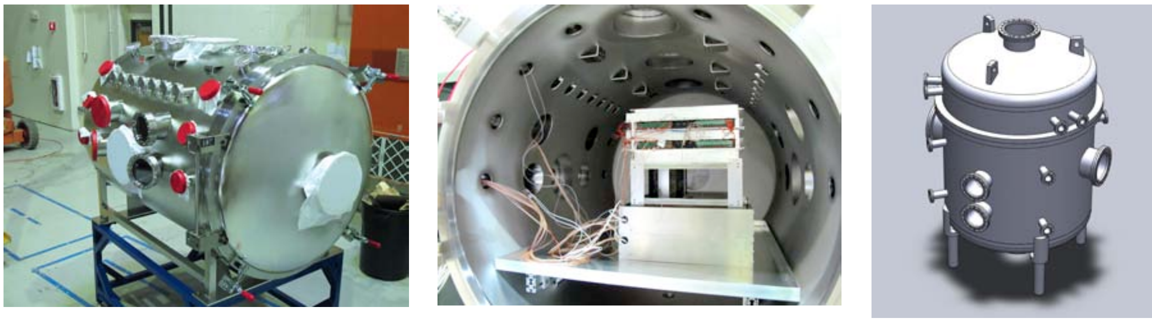


Figure 5. The Lunar Environment and Impact Laboratory chamber exterior (left) and interior (middle) housing a dust-trajectory instrument for testing. This impact chamber will house UV, electron, and ion sources to simulate the variable plasma conditions on the lunar surface, and will act as a target chamber for the dust accelerator. The UHV (right) chamber, designed for experiments of impact products, where ultra-high vacuum conditions are required.

3. Duane Dusty Plasma Laboratory (DDPL)

In addition to the suite of experiments taking place in the LEIL facility, a number of small-scale, rapid turn-around experiments are being conducted at the Duane Dusty Plasma Laboratory on the main University of Colorado campus. The DDPL facility uses several various-sized vacuum chambers, along with a standard suite of plasma diagnostic tools, to analyze and interpret various environments relevant to the lunar near-surface plasma environment. These experiments have focused on demonstrating and investigating the "basic physics" of the lunar plasma environment and associated dust dynamics.

3.1 Dust Transport

When the Moon enters the plasma sheet of the earth, high-energy electron fluxes are incident upon the lunar surface. Some regions are in the shadow of these fluxes due to topographic features. Large electric fields were found at similar shadow boundaries created by the electron beams incident upon an obstacle in the laboratory (**Figure 6**). Potentials on the beam-illuminated surface follow beam energies and were negative relative to potentials on the shadowed surface. Charged dust particles in the beam-illuminated region were observed to move into the shadow due to these electric fields (**Figure 6**). The oblique incidence of the electron fluxes upon craters can lead to a portion of the crater surface in the beam-illumination and another portion in the shadow. Dust particles on the slopes of the craters can thus experience large electric fields and transport downhill to fill the bottom of the craters. This mechanism may contribute to the formation of dust ponds observed by the NEAR-Shoemaker spacecraft at 433 Eros, and might be at work on the lunar surface as well. In the laboratory, we used electron fluxes with energies up to 90 eV to bombard an insulating half-pipe (**Figure 7**). An angle of incidence was chosen so that the impact occurred on far side of the slope and left the bottom and the nearside slope in the shadow. Dust particles on the beam-illuminated slope moved down along the surface toward the bottom of the half-pipe and hopped to the bottom as well, while particles on the shadowed slope remained at rest (**Figure 7**).

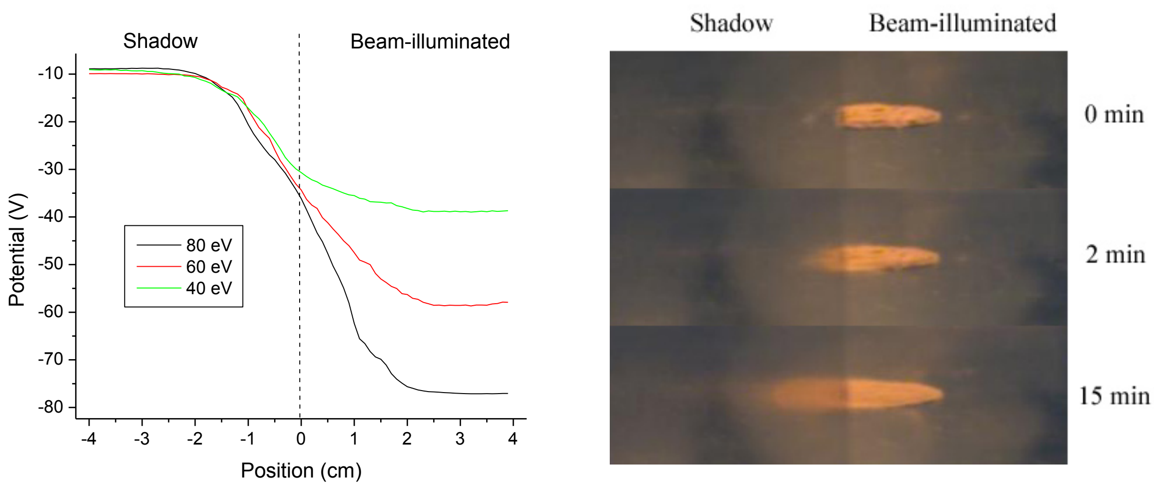


Figure 6. Potential distributions 1mm above the surface across the beam/shadow boundary with three energies (left). Images showing dust transport into shadow with the beam energy at 80eV. The labels indicate the time elapsed after turning on the beam (right).

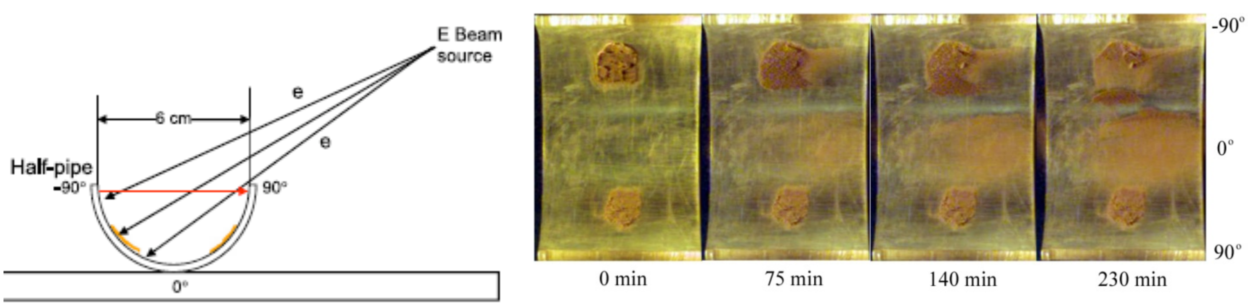


Figure 7. Experimental configuration for dust transport in a half-pipe. Two dust patches are in orange color. The red arrowed-line shows the emissive probe track for the potential measurements (left). Images of dust transport in the half-pipe with the beam energy at 80 eV. The labels indicate the time elapsed after turning on the beam (right).

3.2 Electric fields near craters

Lunar craters have a variety of sizes relative to ambient plasma shielding distance. The electric potential distributions in these craters are significantly different. The experiments were performed with a hemispherical shape crater in the center of a thick insulating disc in the laboratory plasmas. When the sheath S is smaller than the radius of the crater R, the barrier-like potential structures are seen between the central crater and the wall due to the plasma expansion into the crater (**Figure 8**). When the sheath is larger than the radius of the crater, the potential distribution in the crater becomes more homogenous because the plasma is shielded out from the crater (**Figure 8**). Due to the topography of the crater and the plasma shielding effects, the electric fields near the bottom of the crater are relatively small. This result may cause charged dust particles transported into the depression to become trapped, possibly forming the dust ponds observed on asteroid 433 Eros.

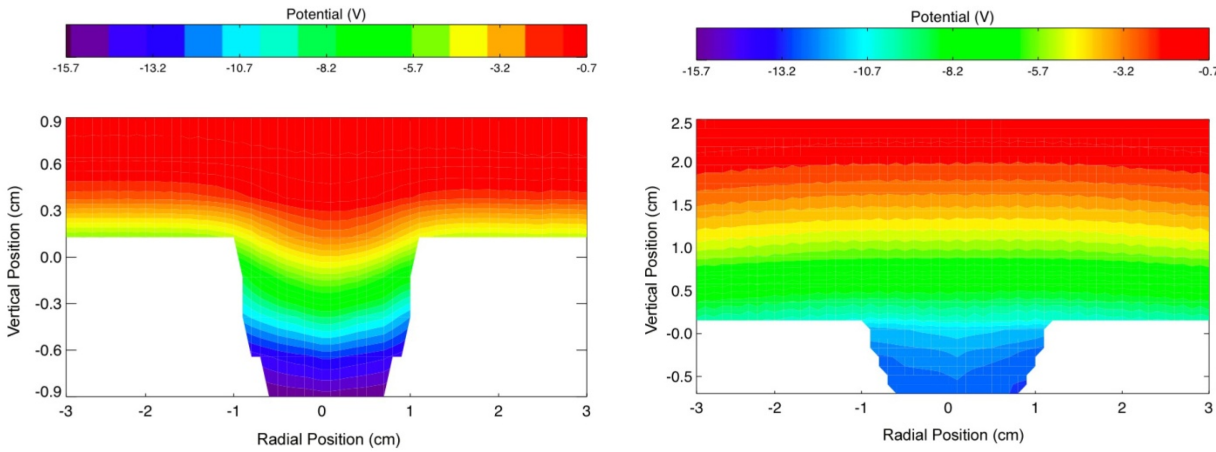


Figure 8. Potential contours in/out a crater: S < R (left) and S > R (right).

3.3 Magnetic field effects on plasma sheaths

Fundamental studies of the effects of the crustal-like magnetic fields on surface charging and the sheath profiles have begun in the laboratory. The magnetic fields are created by a permanent magnet placed below an insulating surface (**Figure 9**). Preliminary results show that the surface charging and the sheath above the surface are largely dependent on the local magnetic field properties. A non-monotonic sheath was seen for the first time in the presence of a magnetic field (**Figure 10**). The gyro-radii for the electrons and ions are < 1 mm and ~ several cm, respectively; therefore, the electrons are thus more magnetized and trapped by the magnetic fields above the surface but the less magnetized ions can still reach the surface, leading to a positively charged surface. Horizontal scans 1 mm above the surface show a complex potential pattern along the magnetic field lines (**Figure 10**).

3.4 Characteristics and diagnostics of a photoelectron sheath

Immediately above the lunar surface is a sheath of photoelectrons with a density much greater than the electron density in the solar wind. In order to better understand the plasma environment of the lunar surface, we constructed an experiment with intense ultraviolet sources to create a sheath of photoelectrons above a surface. Initial studies have been done with metallic surfaces having known surface potentials in order to develop diagnostic probes and to aid in developing methods for interpreting probe data. A second series of experiments are planned for the summer of 2011 in which lunar regolith simulants will be placed on the metallic surfaces.

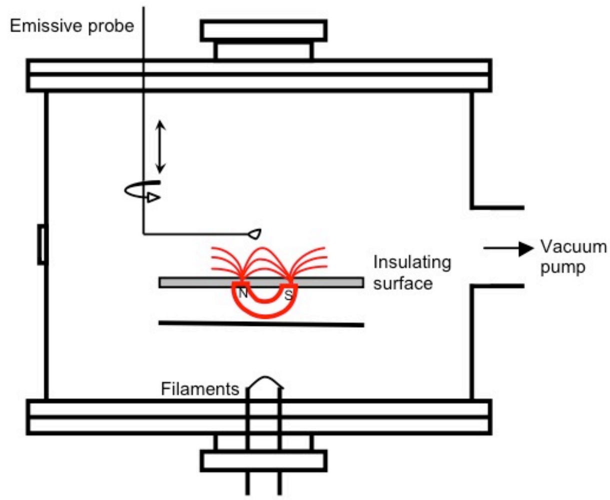


Figure 9. Magnetic field configuration in a small chamber.

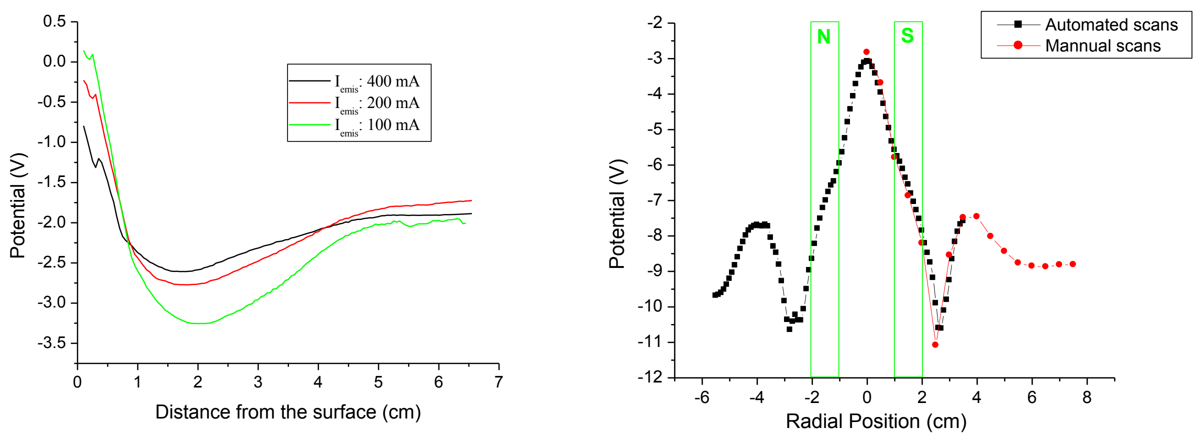


Figure 10. Vertical potential profiles above the surface in the magnetic fields (left). Horizontal potential profile along the magnetic field lines (right).

The experiments are carried out in a 200-liter cylindrical vacuum chamber that is 62 cm in diameter and 82 cm tall (**Figure 11**). The chamber has ports at the top for mounting up to 10 xenon excimer lamps that deliver intense UV at 170 nm (~7 eV photon energy). The emitting surface is a zirconium disk 50 cm in diameter. Above the disk is a stainless steel mesh separated by 7.6 cm. The grid provides a surface of constant potential that aids in data analysis and in comparisons of data with results from simulation codes with idealized boundary conditions. The measurement tools include (1) a small surface of Pt foil with known photoemission coefficients for calibration of the light intensity, (2) a cylindrical Langmuir probe for the electron density and distribution function, and (3) an emissive probe for measurements of the space potential above the surface.

Figure 12 shows the photocurrent density as a function of distance from the top of the chamber with one and two lamps operating. These data show that current densities of order 1 microamp/cm^2 are easily achieved above a metallic surface.

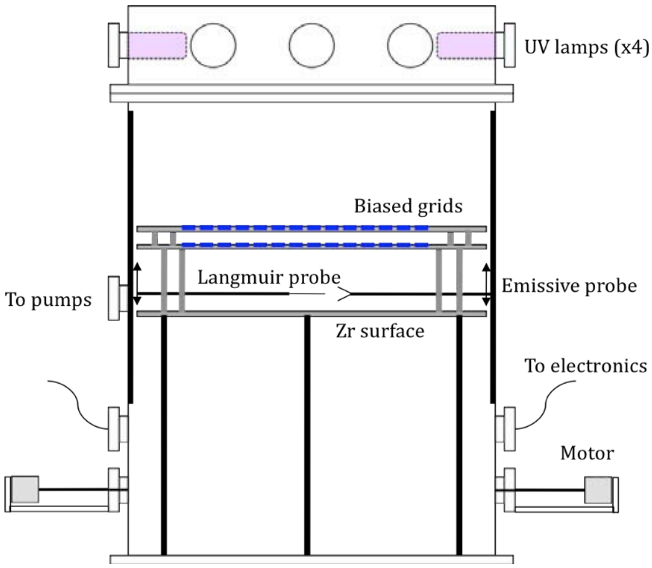


Figure 11: The photoemission experiments are conducted in a vacuum chamber having UV sources at 170 nm. Initial work is done with a 50 cm dia. Zr surface that is beneath grids that are biased to define planar potential surfaces. The photoelectron plasma is measured by a Langmuir probe and the electrostatic potential is mapped by the emissive probe. The grids are biased to repel spurious electrons from the chamber walls

This photoemission current density is greater than at the lunar surface (~4 μA/m^2) so that we can have a sufficiently small Debye shielding distance (<10 cm) in our experiment to observe sheath effects. The sheath must have a Debye length smaller than the characteristic dimensions of the experiment. The Debye length for our photoelectron layer is about 4 cm, which is significantly smaller than the transverse dimensions (~50 cm) of the emitting surface. Hence with only a four of the 10 lamps operating the experiment is well within the regime where shielding effects are observable.

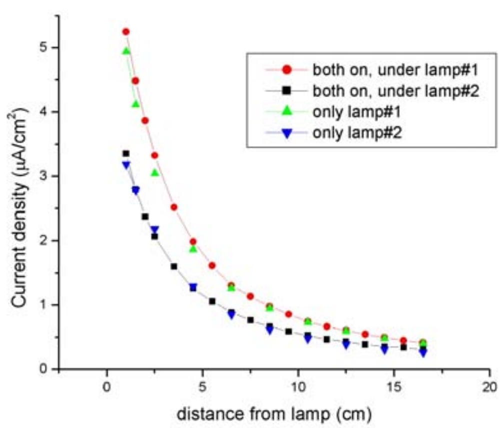


Figure 12: Plot of photoemission from a Zr surface as a function of distance from one and two UV lamps. The photoemission at a typical working distance is of order 1 microamp/cm^2. Photoemission from the lunar surface is about 0.4 nanoamps/cm^2.

Extensive sets of data have been taken with the Langmuir probe that give the photoelectron density and temperature and with the emissive probe that give the potential profile between the emitting surface and the grid. Here we highlight one Langmuir probe dataset showing how it may be used to find the potential of the lunar surface relative to an instrument package. The probe is attractive to electrons when biased positively and repels electrons when biased negatively. The electron distribution is often near-Maxwellian; thus, the current falls exponentially when the probe is negative. The current increases algebraically when the probe is positive. Thus there is a peak in the first derivative when the probe is at the plasma potential. For a probe above the lunar surface emitting photoelectrons, we conjectured that the photoelectrons have a plasma potential corresponding to the potential of the lunar surface. We have verified this conjecture in the data in **Figure 13**. Probe sweeps are taken above the Zr surface with different bias voltages on the surface. The first derivative of the probe sweep moves to more positive potential as the surface is made more positive. The data show that the peak in the first derivative is an accurate measure of the potential of the emitting surface. The remains true over a range of bias voltages from -20 V to +10 V as shown in **Figure 13.**

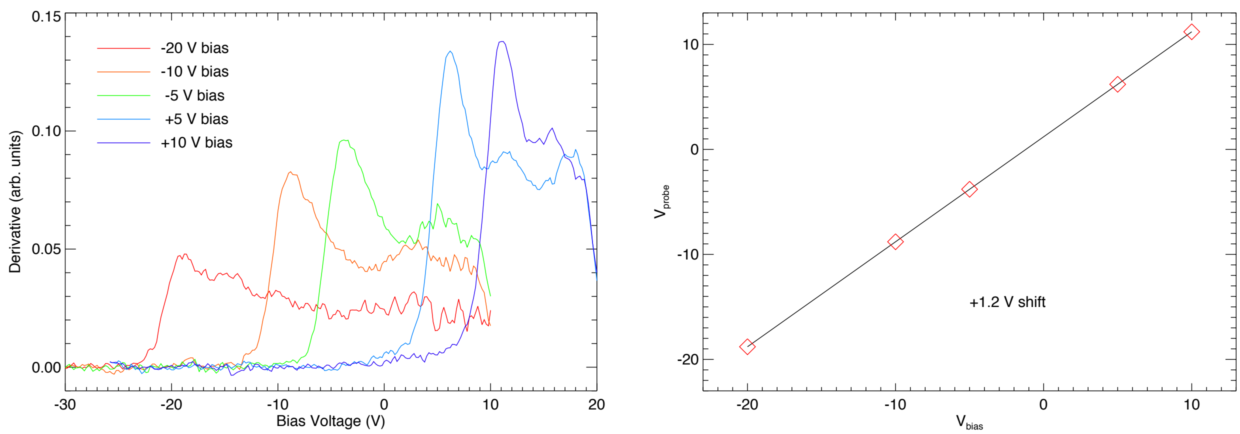


Figure 13. The first derivative of Langmuir I-V characteristic for a probe above a photoemitting surface having an adjustable bias potential. The peak in the first derivative occurs at more positive voltages as the photoemitting surface is made more positive (left). Location of the peak in the derivative of the Langmuir probe I-V characteristic plotted against the potential of the photoemitting surface. The data show that the peak follows the surface bias potential with and offset of about one volt (right)

The photoelectron sheath experiments will continue with surfaces that are partially and totally covered with granular materials. These materials will include conductors, insulators such as cerium oxide with high photoelectron emission, and simulated lunar surface regoliths. Transport of dust will be studied by photographing the change in appearance of surfaces that are partially covered with a dust that has a high visual contrast with the underlying material. Faraday cup collectors will be used to determine the charge on individual grains that are set in motion by electrostatic forces. Data from the Apollo missions showed that dust on the Moon was more mobile near sunrise and sunset, hence these experiments will include a light baffle to create a surface with a gradient in illumination.

4. Instrument Development

4.1 Langmuir Probes for the Lunar Surface (LPLUS)

CCLDAS and its industry partner United Launch Alliance (ULA) co-funded a student instrument development project at the Aerospace Engineering Sciences (AES) Department of the University of Colorado. The ASEN 4018/4028 class was a two-semester course covering the entire instrument development process, ending in the summer of 2010. The course was structured and run as a NASA hardware-project, including the standard milestones: Preliminary Design Review (PDR), and Critical Design Review (CDR). The instrument requirements are derived from a carefully assembled set of science and measurement requirements.

In addition to funding this project, CCLDAS has been involved in educating students in the technical challenges of future lunar missions. The development resulted in a fully tested (TRL = 4) laboratory prototype of the Langmuir Probes for the Lunar Surface (LPLUS) instrument, which consists of one 3 m and two 2 m long deployable booms (**Figure 14**).

Credit for the work is given to group of seven AES undergraduate students: A. Berg, K. Hahn, T. Hanson, L. Martinez, R. Mayerle, M. Siegers, S. Valdez.

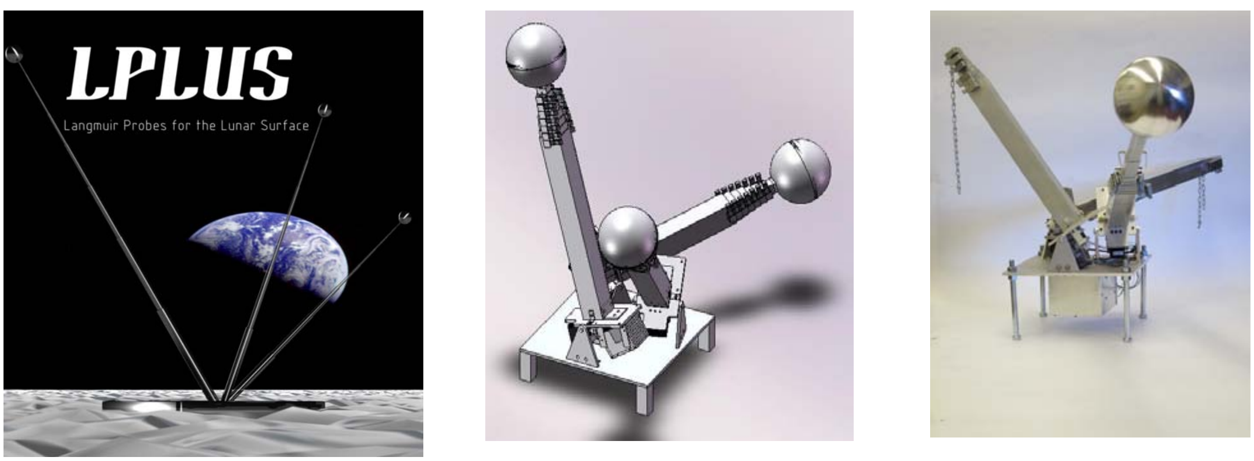


Figure 14. The LPLUS logo developed by the students (left), schematics of the LPLUS deployable boom structure (middle), and the LDEX prototype machined, build and tested by students.

4.2 LPLUS Laboratory Model

A scaled-down version of the LPLUS has been constructed and is undergoing testing in a simulated lunar surface environment including UV illumination and low-density plasma. (**Figure 15**). The initial probe sweep measurements showed that the UV generated photoelectron plasma has a wide electron density distribution that was likely the effect of contamination of the plasma chamber surface. A liner with pristine graphite coating has been designed and is currently under construction.

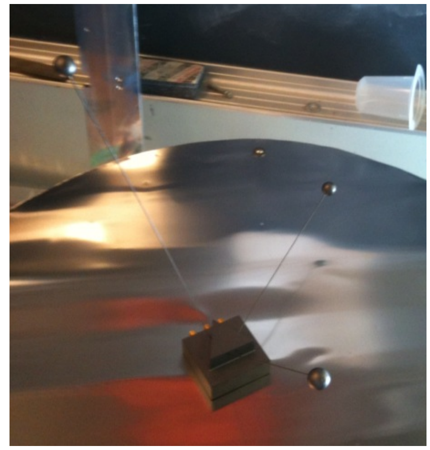


Figure 15. LPLUS$^-$ instrument.

4.2 Electrostatic Lunar Dust Analyzer (ELDA)

This instrument development has been initially funded by the Planetary Instrument Definition and Development Program (PIDDP) to detect and analyze the trajectory of low velocity charged dust particles, such as expected to be present in the near-surface lunar environment. ELDA has been developed to TRL = 4 by testing the laboratory prototype in air. The ELDA operation concept is based on measuring the induced charge from a dust particle on an array of wire electrodes. As part of the CCLDAS instrument development effort, the ELDA instrument development continues for increasing its TRL level by testing and calibrating in a relevant environment. A vacuum-compatible version of the ELDA has been constructed and is under testing in the Lunar Environment and Impact (LEIL) chamber (**Figure 16**). Tests are performed by dropping charged dust particles into ELDA, and measuring its velocity vector and mass. These measurements are being undertaken now and the next step will be to study the performance under UV illumination and exposed to low-density plasma. Parallel to the ELDA hardware activates, a numerical procedure for the analysis of the experimental data is also under development.

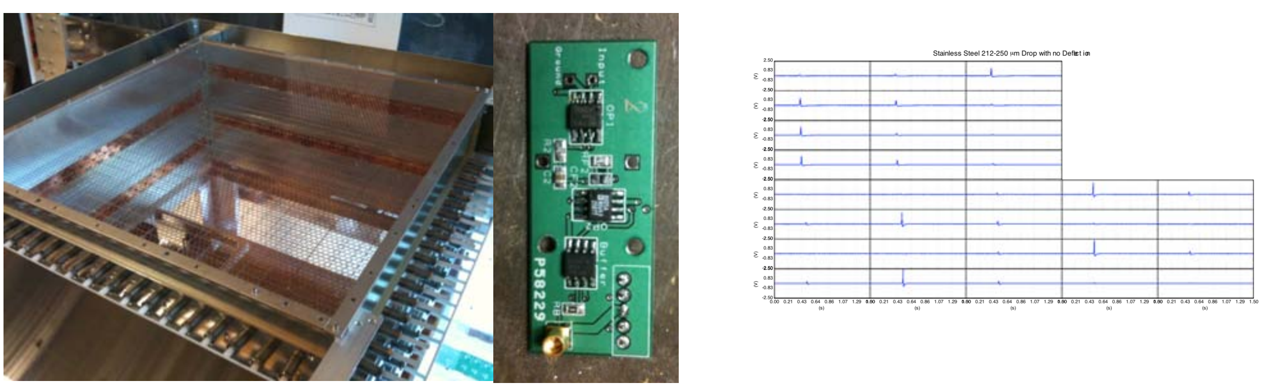


Figure 16. The ELDA instrument tested in the LEIL chamber (left); the newly developed low-noise Charge Sensitive Amplifier (middle), and signals from a slow-speed dust particle as it drops through the position sensitive wire-planes of ELDA (right).

5. Education and Public Outreach

Beginning in October 2010, E/PO management was moved to the new LASP Office of Communications & Outreach manager, Stephanie Renfrow, following the departure of the previous lead, Dr. Emily Cobabe-Ammann. As part of this transition, Renfrow revisited the existing E/PO plan to include updates of programming elements and costs. She and her team also began planning and development of new programs.

5.1 Journalist Workshop

NASA has traditionally identified activities that promote the education of the general public as part of E/PO and those that involve journalists and the media as part of Public Affairs. However, over the last several years, there has been recognition that in the interest of "full spectrum science communication," journalists, who deliver more than 85% of the science news and content to the general public, may be legitimately seen as an audience for E/PO activities. The goal of these activities is not primarily to promote a specific story, event, or theme, but instead to broaden and deepen journalists' understanding of space science and to promote increased communication and understanding among journalists, scientists and educators. It is in our interest to have journalists competently well-informed and captured by the excitement of space sciences and exploration.

The May 2010 journalist workshop carried on a 5-year legacy of media professional development workshop by Dr. Emily CoBabe-Ammann, the CCLDAS E/PO lead through October 2010. The program was attended by 11 nationally recognized journalists and six scientists, as well as an astronaut. Seven areas were covered:

Bill Bottke	SWRI Boulder	NLSI/CLOE	Bombardment History of the Moon
Steven Moijzis	CU Boulder	NLSI/CLOE	The missing history of the Moon
Jasper Halekas	UC Berkeley	NLSI/DREAM	The lunar space plasma environment
Mihaly Horanyi	CU Boulder	NLSI/CCLDAS	Moon: A Dusty Plasma Laboratory
Benjamin Weiss	MIT	NLSI/Brown-MIT	The Possibility of a Lunar Core
Alan Stern	SWRI Boulder	NLSI/CCLDAS	The Future of Lunar Science
Jeff Ashby	Blue Origins		The Future of Lunar Exploration

These workshops, starting in 2011, have been picked up as an NLSI core activity. The first of the NLSI/CCLDAS media workshops set the groundwork for workshops to come. We are focusing on three themes: 1) The current state of our understanding of the Moon system, 2) How we can use the Moon as a place to conduct natural experiments, and 3) Discussion of the direction of lunar exploration, both within NASA and within the commercial space industry.

5.2 Lunar Graduate Conference (LunGradCon 2010)

The first annual Lunar Graduate Conference (LunGradCon 2010) was held at the NASA Ames Research Center in Mountain View, CA, on July 18, 2010, and was a success, with 17 talks and 23 attendees. The goal of LunGradCon 2010 was to enhance the professional development of graduate students and early postdoctoral researchers and engineers in lunar science by providing an opportunity to present and discuss scientific research in an environment of their peers. As such, the conference was planned by and attendance was restricted to current graduate students and early postdoctoral researchers. The two lead organizers for LunGradCon 2010, Andrew Poppe and Adrienne Dove, are both graduate students at CCLDAS. The organizing committee also included a graduate student at Notre Dame working with Clive Neal, Amy Fagan, and a postdoc working at the Applied Physics Laboratory with Ben Bussey, Catherine Neish.

The students in attendance all had the chance to present their work in a “low-stress” environment in order to improve their speaking ability and confidence. Additionally, many of the graduate students formed connections with students in other fields and at other universities and institutions, which will help to strengthen their future careers in lunar science. The planning for LunGradCon 2011 is underway, with a combination of organizers from LGC 2010 and new organizers from various institutions.

5.3 International Observe the Moon Night (InOMN 2010)

Saturday, September 18, 2010, marked the first annual International Observe the Moon Night. InOMN is an outreach event created to get the public interested in the Moon, give them a chance to look through telescopes and learn about the Moon, and see how exciting current lunar research can be. Adrienne Dove organized a CCLDAS event at the Courthouse Lawn on the Pearl Street Mall in downtown Boulder, CO (**Figure 17**). Many CCLDAS members were in attendance, including professors, researchers, and graduate and undergraduate students; other graduate students from CU helped out at the event, as well. Two homemade reflecting telescopes (with 15” and 17” primary mirrors) were set up on the lawn and aimed at the Moon and at Jupiter (which nicely had the four Galilean moons in full view) throughout the night. At least 200 people stopped by and “oohed” and “ahhed” as they peered through the eyepieces; for many it was their first time looking at the Moon through a telescope. We had a small telescope building activity for kids, led by CCLDAS graduate students, and a couple of other hands-on activities. A slide show of Moon facts was running for most of the evening, and Kim Ennico of NASA Ames presented a short talk on the LCROSS mission. The reception from the public was fantastic - we considered the event a great success, and we look forward to an even grander event next year!

Figure 17. On September 18, 2010, in downtown Boulder, a line of people gazed at the Moon with their homemade telescopes, most of which were built by K-12 students, but enjoyed by all ages!

5.4 Public Talks

1. Dust in Space – What Can We Learn from It?, Z. Sternovsky, LASP public lecture, May 5, 2010
2. Mysterious Moving Moon Dust, M. Horanyi, 365 days of Astronomy Podcast on November 23, 2010
3. CU scientist and Vice Chancellor for Research Stein Sture made presentations at Boulder Valley School District's Platt Middle School on Nov. 5, 2010, to give two lectures on the same day to different classes on science and engineering research. Each presentation involved a full class period and included work in CCLDAS and science in general.
4. IN PREPARATION: Public Symposium on 4/29/2011.
   The event will feature speakers Elon Musk and Alan Stern, discussing the future of commercial spaceflight. We expect about 400 people to attend this event.

5.5 Online Presence

In addition to public talks and symposia, CCLDAS also maintains a robust online presence in order to connect with the public through "new media", including:

1. Webpages: http://lasp.colorado.edu/ccldas/
2. Student Blog: http://ccldas.blogspot.com/
3. Flickr: www.flickr.com/photos/ccldas/
4. Webcam: http://dustcam.colorado.edu

6. Undergraduate and Graduate Education

6.1 Courses

1. *Graduate Planetary Seminar*: CCLDAS, in partnership with the Lunar University Network for Astrophysical Research (LUNAR) at the University of Colorado and the Center for Lunar Evolution and Origin (CLOE) at the Southwest Research Institute, offered a graduate seminar class in lunar science during the Spring 2010 semester. The seminar covered all three main aspects of NASA's Lunar Science Institute: Of the Moon, On the Moon and From the Moon.
2. *Graduate Plasma Physics*: The Physics Department at the University of Colorado offers a yearly graduate course in plasma physics. The PHYS 5150 now includes a section on dusty plasma physics and was taught by M. Horanyi (Spring 2010), and S. Robertson (Spring 2011).
3. *Aerospace Engineering Senior Project*: The ASEN 4018/4028 was a two-semester course covering the entire instrument development process, ending in the summer of 2010. The course was structured and run as a NASA hardware-project (see description in section 4.1).

6.2 Research

CCLDAS research involves both undergraduate and graduate students. Our experimental students learn to maintain and use vacuum systems, computerized data collection, and most of them has taken a week-long machining class to safely use power tools, including our on-site mill.

Graduate Students	
Addie Dove	DDPL Photoelectron sheath experiments
Andrew Poppe	Theory and modeling
Anthony Shu	LEIL Impact phenomena
Jamey Szalay	LDEX Theory support
Jianfeng Xie	ELDA Theory support
Undergraduate Students	
Christopher Anaya	LEIL Beam line mechanical design and fabrication
Nicholaus Beaty	LEIL Beam line development
Spenser Burrows	Electronics Design and Fabrication
Nicole Duncan (graduated)	Detector Electronics Design
Shannon Dickson	DDPL Plasma diagnostics
Huy Le	ELDA Prototyping
Spencer Leblanc	LEIL Beam line mechanical design and fabrication
Paige Northway	LEIL Charged dust focusing design and fabrication
Marcus Piquette	Theory and modeling
Evan Thomas	LEIL FPGA Design for particle selection
Hemal Semwal	LEIL Beam line development
Todd Strong	Dust Adhesion Experiment Design
Michael Wagner (graduated)	Electronics Design and Fabrication
High School Students	
Jordan Stern	Summer intern

7. NJSC Light Gas Gun Laboratory

The Experimental Impact Laboratory (EIL) at the Johnson Space Center is a facility dedicated almost exclusively to planetary-science research. In rare cases, such as the investigation immediately following the Columbia disaster, EIL personnel and capabilities have supported impact and vacuum testing of spacecraft hardware. The EIL is part of the Astromaterials Research Office (Code KR) of the Astromaterials Research and Exploration Science Directorate (ARES). Scientific and technical support is provided by Jacobs Technology and their subcontractors. The EIL comprises a machine shop and other equipment supporting three separate and distinct ballistic ranges: the flat-plate accelerator (FPA), the two-stage light-gas gun (LGG), and the vertical gun.

1. The FPA is a horizontally mounted, powder-propellant gun used primarily for shock-recovery experiments, in which samples are subjected to predetermined shock stresses, recovered, and analyzed. It uses interchangeable barrels with bores of 20, 25, and 40-mm (diameter).
2. The horizontally mounted LGG uses a gunpowder-driven piston to compress gaseous hydrogen, which is used as the working gas to accelerate 5-mm projectiles to speeds as high as 8 km s^{-1}, although speeds below 7 km s-1 are more typical and less stressful on the equipment.
3. The vertical gun is another powder-propellant accelerator, oriented to shoot vertically downward, permitting experiments using granular and liquid targets. It also uses a variety of interchangeable barrels; those used most often have 6-mm and 7.62-mm bores. Depending on the projectile mass, operational speeds from the vertical gun range up to ~2.8 km s^{-1}. The impact chamber of the vertical gun is a surplus environmental test chamber from the Apollo era, with a built-in refrigeration system that can maintain a chamber temperature of -20°C, thus permitting experiments using cold targets, including H_2O ice.

Installation of a new vacuum plumbing was completed on 9 February of this year on which date it also passed its leak test by a factor-of-two margin (**Figure 18**).

The Experimental Impact Laboratory has been effectively non-operational since April 2008. After more than two years of repair activity, operational shots with the vertical gun will resume during the first week of March 2011. We anticipate that the flat-plate accelerator will be back on line within two weeks of the vacuum-system's completion —by the end of March or in early April. While a prediction for the much more complex light-gas gun is more difficult, we expect that it will take about a month after the FPA is operational before the LGG is ready for science. We will be support CCLDAS experimentation with the vertical gun later this spring or during the summer, and the LGG should be ready by mid-summer.

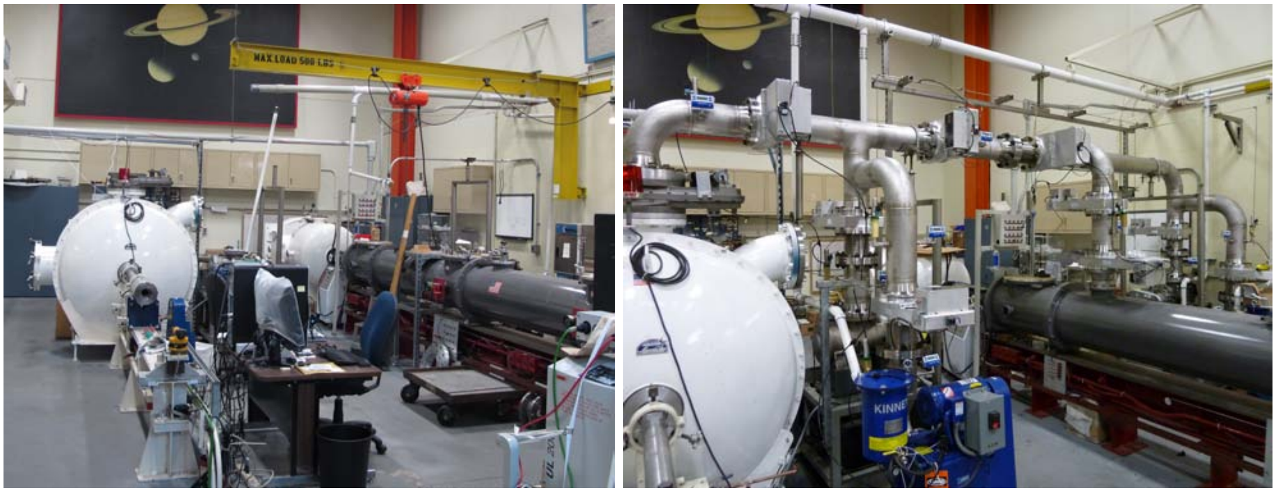


Figure 18. Before the update: The flat-plate accelerator (left) and light-gas gun (right) before installation of the new vacuum plumbing (left). The new vacuum plumbing in place on the flat-plate accelerator (blast chamber on the extreme left) and the light-gas gun (free-flight chamber on the right). Vent lines for the vacuum pumps have been installed and the pneumatic lines have been partially completed in this photograph (right).

8. Tech-X: Large Scale Computational Modeling

Over the past year, Tech-X has been working on two main lunar dust environment simulation scenarios: The first was related to the plasma sheath formation and the resulting electrostatic fields in complex settings like a lunar crater. One of the main questions was to investigate the effect of varying angle of incidence onto the crater and the effect on the resulting fields. To our knowledge, these simulations were the first fully 3D kinetic simulations of the lunar plasma environment in complex geometries. The resulting field patterns were then used by our collaborators at CCLDAS to investigate the transport of a dust particle in the electrostatic field. The second set of simulations was to reproduce experiments of a simpler setup consisting of a plate with a circular dimple and to compare the simulation results to the measured data.

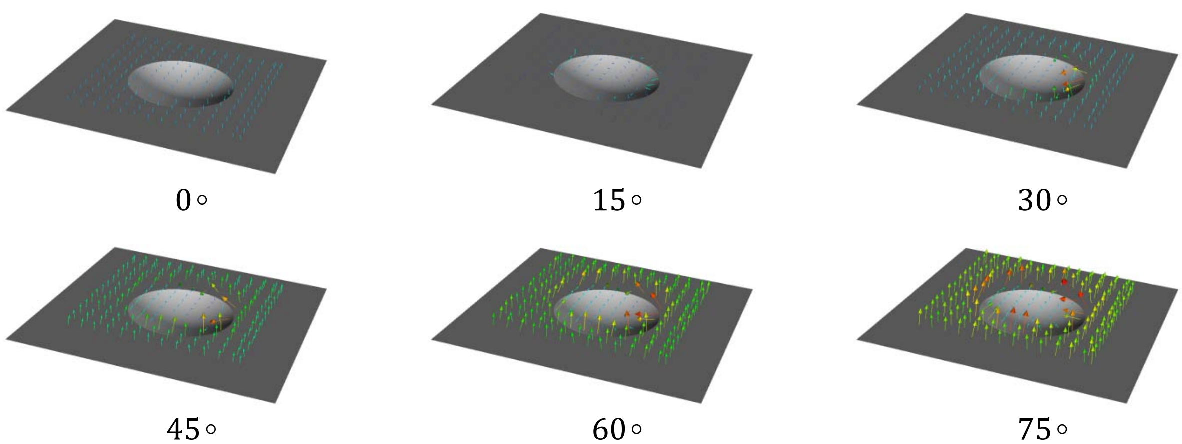
8.1 Simulations of the plasma environment of a lunar crater

The goal of this technical activity was to extend the simulations, designed during the first year of the project, to the simulations of the plasma environment in realistic lunar crater. The crater was modeled as a capped parabola on the flat lunar surface. The crater is assumed to be a perfect dielectric, resulting in immobile charge being accumulated on the crater surface. Photo-emission is represented as a particle source emitting electrons at a rate dependent on the angle between the incident solar radiation and the local surface normal. The incident solar wind is modeled as an electron/proton plasma with parameters commonly found in the solar wind. We performed simulations at various angles of incidence. These simulations were usually run in parallel on 64 cores of an in-house cluster at Tech-X. Each simulation performed 10000 time-steps in about 8 hours and produced a data output of 10 GB. Each simulation ran on a grid of 150x150x150 cells and used $\sim 10^7$

particles. In order to validate the results, we performed a range of simulations at varying grid resolution and varying particle densities.

The main finding from these simulations was the complex structure of electric field at the crater surface. Both the magnitude and the amplitude of the electric field have a strong dependence on the angle of solar incidence (**Figure 19**). These small-scale intense electric fields are expected to have profound effects on the motion of mobilized small charged dust grains (**Figure 20**). It is worth pointing out several key results of the simulations. During the sunrise or sunset, when the solar wind is parallel to the crater surface, neither photons nor solar ions penetrate into the crater; however, thermal solar electrons can enter the crater. These electrons charge the crater surface negatively and lead to a negative surface potential. Electric field lines are directed towards the crater surface. In the opposite case, when the sun is at the zenith, we observe the expected formation of a plasma sheath with positive surface potential and electric field lines pointing from the surface. We also observe the increase in the electric field strength at the crater rim. The next steps in this project are to introduce small objects like a rock into the crater simulations to break the symmetry and observe the effect on the plasma environment. Most of these simulations can be performed with relatively small modifications to the existing simulation setups.

Finally, we conducted a study of the dependence of the plasma sheath near the crater on the external magnetic field. The magnetic field strength varied from 2.5 to 250 nT, corresponding to typical conditions on the lunar surface. However, no effect on the plasma sheath has been observed, most likely due to the significant difference between the Larmor radius for charged particles in such magnetic field (kilometer scale) and the plasma sheath length (meter scale).



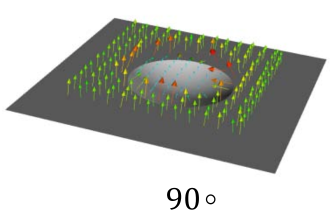


Figure 19. Distribution of electric field on the crater surface for different angles of solar incidence (0 and 90 degrees correspond to solar wind parallel and normal to crater surface).

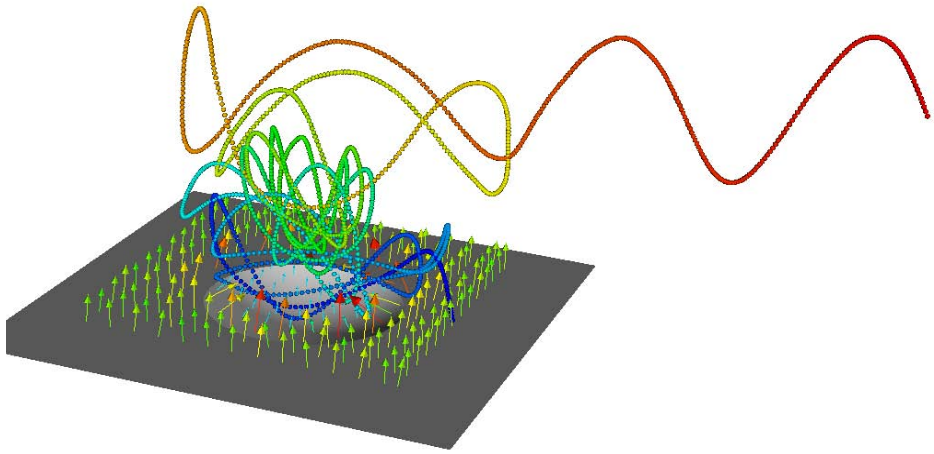


Figure 14. Dust particle trajectory above a crater. The grain starts at right (red points), oscillating stably above the lunar surface. As the grain enters the region above the crater at later times (yellow to blue points), the grain is trapped by the near-surface electric fields. Eventually, the grain comes to rest on the surface inside the crater.

8.2 Simulation Support of Small-scale Laboratory Experiments

In these simulations, a dielectric plate with hemispherical dimple is immersed in a plasma (experimental setup from **Figure 8**). In the experiment, measurements of the potential above the dimple showed the formation of a sheath. The goal of the simulations is to reproduce the sheath measurements. One of the main challenges in setting up these simulations is the large size of the experimental setup and the limited domain size for the simulations. This requires an appropriate setup of boundary conditions in the simulations. In order to prevent charge build up at the domain boundaries, we therefore decided to use reflecting boundaries for the outer walls. However, due to the absorption of some of the plasma on the dimple surface, we needed to introduce additional plasma into the system. The simulation results match qualitatively well with the measurements.

9. Scientific Productivity

9.1 Publications in Refereed Journals

1. D. James, V. Hoxie, M. Horanyi, Polyvinylidene Fluoride Dust Detector Response to Particle Impacts, Rev. Sci. Instruments, **81**, 034501, 2010.
2. A. Poppe, M. Horanyi, Simulations of the Photoelectron Sheath and Dust Levitation on the Lunar Surface, J. Geophys. Res. **115**, A08106, doi:10.1029/2010JA015286, 2010
3. S. Auer, G. Lawrence, E. Grün, H. Henkel, S. Kempf, R. Srama, Z. Sternovsky, A self-triggered dust trajectory sensor, Nucl. Instrum. and Meth. A, doi:10.1016/j.nima.2010.06.091, 2010.
4. A. Poppe, B. Jacobsmeyer, D. James, M. Horanyi, Simulation of Polyvinylidene Fluoride Detector Response to Hypervelocity Particle Impact, Nucl. Instr. Meth. A, **622**, 583-587, 2010
5. X. Wang, M. Horanyi, S. Robertson, Investigation of dust transport on the lunar surface in a laboratory plasma with an electron beam, J. Geophys. Res., **115**, A11102, doi:10.1029/2010JA015465, 2010
6. Horányi, Mihály; Havnes, Ove; Morfill, Gregor E., Dusty plasmas in the solar system, in: Complex and Dusty Plasmas: From Laboratory to Space, Edited by Vladimir E. Fortov and Gregor E. Morfill. Published by CRC Press/Taylor & Francis, Boca Raton 2010. ISBN: 9781420083118, p.291
7. A. Poppe, J. S. Halekas, and M. Horanyi, Negative potentials above the day-side lunar surface in the terrestrial plasma sheet: evidence of non-monotonic potentials, Geophys. Res. Lett., **38**, L02103, 2011

9.2 Refereed Publications in Press

1) X. Wang, M. Horanyi, S. Robertson, Dust transport near electron beam impact and shadow boundaries , Planetary and Space Science, in press, 2011
2) E. Grün, M. Horanyi, and Z. Sternovsky, The Lunar Dust Environment, Planetary and Space Science, in press, 2011
3) F. Postberg, E. Grün, M. Horanyi, S. Kempf, H. Krueger, R. Srama, Z. Sternovsky, and M. Trieloff, Compositional Mapping of Moon Surfaces by Mass Spectrometry of Dust Ejecta, Planetary and Space Science, in press, 2011
4) X. Wang, M. Horanyi and S. Robertson, Dust Transport on a Surface in Plasma, IEEE Transactions on Plasma Science, in press, 2011
5) N. Duncan, Z. Sternovsky, E. Grün, S. Auer, M. Horanyi, K. Drake, J. Xie, G. Lawrence, D. Hansen, The Electrostatic Lunar Dust Analyzer (ELDA) for the detection and trajectory measurement of slow dust particles on the lunar surface, Planet. Space Sci. 2011
6) Dove, A., G. Devaud, X. Wang, M. Crowder, A. Lawitzke and C. Haley, (2011), Mitigation of lunar dust adhesion by surface modification, Planet. Space Sci., in press.

9.3 Published Conference Proceedings and Abstracts

1) G. T. Delory, R. C. Elphic, A. Colaprete, P. Mahaffy, M. Horanyi, The LADEE Mission: The Next Step After the Discovery of Water on the Moon, 41st Lunar and Planetary Science Conference (2010), Abstract #2459
2) A. Dove, S. Dickson, S. Robertson, Z. Sternovsky, X. Wang, M. Horanyi, Characterization of a UV-generated Photoelectron Sheath, 41st Lunar and Planetary Science Conference (2010), Abstract #2406
3) A. R. Poppe, M. Horanyi, Simulations of the Lunar Photoelectron Sheath and Associated Dust Grain Levitation Equilibria, 41st Lunar and Planetary Science Conference (2010), Abstract #1218
4) Munsat, T.; Sternovsky, Z.; Robertson, S.; Grün, E.; Horanyi, M.; Lunar Dust Transport Package; 41st Lunar and Planetary Science Conference, held March 1-5, 2010 in The Woodlands, Texas. LPI Contribution No. 1533, p.2538
5) Poppe, A. R.; James, D.; Jacobsmeyer, B.; Horányi, M.; Measurements of the Interplanetary Dust Population by the Venetia Burney Student Dust Counter on the New Horizons Mission; 41st Lunar and Planetary Science Conference, held March 1-5, 2010 in The Woodlands, Texas. LPI Contribution No. 1533, p.1219
6) A. Likhanskii, A. Poppe, M. Piquette, P. Messmer and M. Horanyi, Plasma Sheath at Moon Craters: from Sunrise to Sunset, 42nd Lunar and Planetary Science Conference (2011), Abstract # 2285
7) M. Horanyi, Z. Sternovsky, E. Grun, S. Kempf, R. Srama, F. Postberg, LDEX+ Lunar Dust Experiment with Chemical Analysis Capability to Search for Water, 232, 42nd Lunar and Planetary Science Conference (2011), Abstract #1656
8) A. Dove, S. Robertson, X. Wang, A. Poppe, Z. Sternovsky, and M. Horanyi, Characterization of a Laboratory Simulated Lunar Photoelectron Sheath, 234, 42nd Lunar and Planetary Science Conference (2011), Abstract #2650
9) Z. Sternovsky, E. Grün, K. Drake, J. Xie, M. Horanyi R. Srama, S. Kempf, F. Postberg, A. Mocker S. Auer, H. Krüger, Novel Instrument for Dust Astronomy: Dust Telescope, IEEE Aerospace Conference Proceedings, (2010)

9.4 Colloquia and Talks at Scientific Meetings

1. INVITED TALK: 'A Short History of Dust Accelerators', T. Munsat, 21st International Conference on the Application of Accelerators in Research and Industry (Fort Worth Texas), Aug. 8-13, 2010
2. INVITED TALK: 'In Situ Measurements of Interplanetary and Interstellar Dust', M. Horanyi, UC Irvine, CA (03/2010)
3. INVITED TALK: 'Charged dust in the Solar System: Direct and Indirect Evidence', M. Horanyi, AAS, Miami, FL (5/2010)
4. INVITED TALK: 'Plasma Physics of the Lunar Surface', M. Horanyi, ICTP, Trieste, Italy (7/2010)
5. INVITED TALK: 'The Lunar Surface: A Dusty Plasma Laboratory', Robotic Science From the Moon: Gravitational Physics, Heliophysics and Cosmology, T. Munsat, (10/2010), Boulder, CO

6. INVITED TALK: 'Investigation of near-surface lunar dust transport in the laboratory', Z. Sternovsky, 38th COSPAR Scientific Assembly, 18 – 25 July 2010, Bremen, Germany
7. NLSI SEMINAR: 'The lunar surface: a dusty plasma laboratory', Z. Sternovsky, NLSI Director's Virtual Seminar Series, November 8, 2010
8. NLSI SEMINAR: "Plasma physics of the lunar surface", A. Poppe, NLSI Director's Virtual Seminar Series, May 18, 2010
9. Nano-Dust Analyzer; Gruen, E.; Horanyi, M.; Moebius, E.; Sternovsky, Z.; Auer, S.; Srama, R.; Juhasz, A.; American Geophysical Union, Fall Meeting 2010, abstract #SH11B-1673
10. Non-monotonic potentials above the lunar surface: implications for electron reflectometry measurements; Poppe, A. R.; Halekas, J. S.; Horanyi, M.; American Geophysical Union, Fall Meeting 2010, abstract #P54B-08
11. Experimental Investigations of the Lunar Photoelectron Sheath; Dove, A.; Sternovsky, Z.; Wang, X.; Robertson, S. H.; Lapanse, C.; Horanyi, M.; Collette, A. ; American Geophysical Union, Fall Meeting 2010, abstract #P51C-1460
12. An Ion Analyzer for the Lunar Surface with E Parallel to B; Robertson, S. H.; Collette, A.; Horanyi, M.; Munsat, T.; Sternovsky, Z.; American Geophysical Union, Fall Meeting 2010, abstract #P51C-1455
13. 3D Particle-In-Cell (PIC) simulations of plasma sheath formation above lunar craters; Likhanskii, A.; Poppe, A. R.; Piquette, M.; Amyx, K.; Messmer, P.; Horanyi, M.; American Geophysical Union, Fall Meeting 2010, abstract #P51C-1454
14. Dust transport and electric field distributions in planetary craters; Wang, X.; Horanyi, M.; Robertson, S. H.; Poppe, A. R.; Likhanskii, A.; American Geophysical Union, Fall Meeting 2010, abstract #P51C-1453
15. The Colorado Center for Lunar Dust and Atmospheric Studies; Collette, A.; Gruen, E.; Horanyi, M.; Munsat, T.; Poppe, A. R.; Robertson, S. H.; Srama, R.; Shu, A. J.; Sternovsky, Z.; Wang, X.; American Geophysical Union, Fall Meeting 2010, abstract #P51C-1449
16. The Dust Accelerator Facility at CCLDAS; Shu, A. J.; Collette, A.; Drake, K.; Gruen, E.; Horanyi, M.; Leblanc, S.; Munsat, T.; Northway, P.; Robertson, S. H.; Srama, R.; Sternovsky, Z.; Thomas, E.; Wagner, M.; American Geophysical Union, Fall Meeting 2010, abstract #P33C-1581
17. The Electrostatic Lunar Dust Analyzer (ELDA) for the detection and trajectory measurement of slow dust particles; Xie, J.; Duncan, N. A.; Sternovsky, Z.; Gruen, E.; Auer, S.; Horanyi, M.; Drake, K.; American Geophysical Union, Fall Meeting 2010, abstract #P33C-1580
18. Dust Telescopes and Active Dust Collectors: Linking Dust to Their Sources; Drake, K. J.; Sternovsky, Z.; Gruen, E.; Srama, R.; Auer, S.; Horanyi, M.; Kempf, S.; Krueger, H.; Postberg, F.; ; American Geophysical Union, Fall Meeting 2010, abstract #P33C-1579
19. LDEX-PLUS: Lunar Dust Experiment with Chemical Analysis Capability to search for Water; Horanyi, M.; Sternovsky, Z.; Gruen, E.; Kempf, S.; Srama, R.; Postberg, F.; American Geophysical Union, Fall Meeting 2010, abstract #P11C-1353
20. The Dust Accelerator Facility at CCLDAS; Shu, Anthony; Collette, A.; Cosentino, R.; Drake, K.; Duncan, N.; Horanyi, M.; Leblan, S.; Munsat, T.; Northway, P.; Robertson, S.; Sternovsky, Z.; Thomas, E.; Wagner, M.; Wingfield, T.; Grun, E.; Srama, R.; American

Physical Society, 52nd Annual Meeting of the APS Division of Plasma Physics, November 8-12, 2010, abstract #CP9.032

21. The Lunar Atmosphere and Dust Environment Explorer (LADEE): New Mission, Longstanding Questions; Elphic, R. C.; Delory, G. T.; Grayzeck, E. J.; Colaprete, A.; Horanyi, M.; Mahaffy, P.; Hine, B.; Boroson, D.; Salute, J. S.; Annual Meeting of the Lunar Exploration Analysis Group, held September 14-16, 2010 in Washington, DC. LPI Contribution No. 1595
22. A Novel Suborbital Experiment for Studying the Global Distribution of Levitated Lunar Terminator Dust, A. Stern, M. Horanyi, 2011 Next-Generation Suborbital Researchers Conference, Orlando, FL (3/2011)
23. Program of the Colorado Center for Lunar Dust and Atmospheric Sciences, T. Munsat, M. Horányi, S. Robertson, Z. Sternovsky, and the CCLDAS Team, NLSI Lunar Science Conference, Moffett Field, CA, July 19-22, 2010.
24. The Dust Accelerator Facility at CCLDAS, A. Shu, A. Collette, R. Cosentino, K. Drake, N. Duncan, E. Grun, M. Horányi, S. LeBlanc, T. Munsat, P. Northway, S. Robertson, R. Srama, Z. Sternovsky, E. Thomas, M. Wagner, T. Wingfield , NLSI Lunar Science Conference, Moffett Field, CA, July 19-22, 2010.

9.5 Undergraduate Research Conference in Planetary Science (3/2011) Presentations

1. Electrostatic Effects on Dust Transport in the Lunar Plasma Environment. M. Piquette, A. Poppe, M. Horanyi, P. Messmer, and A. Lihkanskii
2. Beam Line Focusing and Alignment for a New Dust Particle Accelerator, Northway P., Auer S., Drake K., Grün E., Horányi M., Munsat T., Thomas E., Shu A.
3. Dust Detection for a Lunar Dust Accelerator, Thomas E., Shu A.. Collette A., Drake K, Munsat T., Horányi M., Sternovsky Z.

10. Collaborations with NLSI Teams

10.1 DREAM and CCLDAS

Andrew Poppe and Mihaly Horanyi (CCLDAS) worked with Jasper Halekas, Greg Delory, and Bill Farrell (DREAM) on the analysis and interpretation of observations made by Lunar Prospector (LP) of the lunar surface potential in both the terrestrial plasma sheet and the solar wind. The Electron Reflectometer on LP reported large negative surface potential over the lit side of the Moon, contradicting all theoretical expectations. Recently developed theoretical and simulation models suggest the formation of a non-monotonic potential structures above the dayside lunar surface with a large negative potential minimum above the surface, while still maintaining a positive charge density of the surface, offering a long-awaited theory to explain the LP findings. This collaboration resulted in publication #7, and a manuscript submitted for review in a special issue on plasma interaction with non-magnetized bodies in the journal *Earth, Planets and Space*.

10.2 LUNAR and CCLDAS

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

10.3 International Partners

CCLDAS closely collaborates with the dust group at the Max-Planck-Institute for Nuclear Physics, Heidelberg, and the University of Stuttgart, Germany. CCLDAS greatly benefited from these collaborations in the development of our dust accelerator facility. We are currently working on establishing a common data management system for dust impact studies, and plan on scheduling parallel complementary experiments. We have an active exchange program for postdocs and researchers, and initiated establishing a student exchange program that will also include formal class work, in addition to involvement in our experimental programs.