Research Campaign White Paper

Lunar Dust and Plasma Research Lab

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Summary

Significant experimental and computational investigations have explored the feasibility of electrostatically-driven dust motion on the lunar surface. The motion of lunar dust influences our understanding of the evolution of the surface and may also present a hazard to future exploration vehicles and astronauts. The possibility of a sustained exploration presence on the lunar surface opens the door to long-term experiments on the lunar surface, akin to the science facilities on the International Space Station. We have identified four experiments that would significantly advance our understanding of dust-plasma interactions on the lunar surface, as recommended in the recent ARTEMIS III Science Definition Team report. In this whitepaper, we provide conceptual designs and implementation plan for the following payloads: (1) near surface lunar plasma probe, (2) lunar dust charge detector, (3) lunar dust transport monitor, and (4) lunar horizon glow observer. To accommodate these and subsequent science payload concepts, we propose to develop a common facility, named the Lunar Dust and Plasma Research Lab (LDPRL), that can be deployed by an Artemis astronaut on the lunar surface, or by a CLPS mission. The LDPRL will have a portable, field deployable equipment rack with common power system, solar panels, batteries, thermal management, communication, data handling, a standard bus interface architecture for exchangeable science payloads, and Artemis Human Landing System (HLS) interface and/or a CLPS lander interface. Telescience will be used for real-time control of the experiments. The LDPRL would be active for 3 mo to characterize the lunar-dust plasma environment at different illumination conditions.

Motivation

Due to its lack of significant atmosphere or global magnetic field, the lunar surface interacts directly with the solar wind plasma and solar UV radiation. This interaction causes charging of the surface regolith particles and the formation of a plasma sheath, which shields the charged surface from the quasi-neutral freestream plasma. There is also an electric field in the plasma sheath. The interaction of the electric field with the charged regolith particles causes an electrostatic force on the particles, which may cause or influence particle motion. There are four overarching questions associated with electrostatically motivated dust motion:

- What are the fundamental properties of the plasma sheath and particle charging in a low density plasma?
- Does electrostatic lofting/levitation occur (naturally, or in response to exploration activities)?
- Does electrostatic dust motion contribute significantly to the evolution of the lunar surface?
- Does electrostatic dust motion pose a hazard to exploration activities?

Electrostatically motivated dust motion was initially hypothesized during the Apollo and Surveyor eras [16], and recent observations by the Chang'E-3 mission provide additional supporting evidence [22]. However, there is no conclusive evidence that electrostatic lofting of particles occurs. If electrostatic lofting does occur, it would modify the dust flux and size distribution of particles deposited on exploration vehicles, potentially posing a hazard to those vehicles. Likewise, the redistribution of regolith grains may influence the evolution of the lunar surface. There have been many terrestrial experimental and computational investigations [20, 21, 17, 15, 9, 8] of particle charging, plasma sheath formation, structure and evolution, and electrostatic dust motion on the Moon. Terrestrial experiments are not able to recreate the plasma temperatures and densities present on the lunar surface. Thus, the lunar surface presents a unique laboratory to investigate low density plasmas and in situ measurements would test/calibrate existing models of the near surface plasma environment. Additionally, the same plasma-dust interactions have been hypothesized to occur on asteroids and planetary rings as well [7, 10]. Thus, investigations of plasma-dust interactions on the lunar surface will also inform our understanding of the evolution of other planetary systems.

Additionally, dust-plasma interactions on the lunar surface are also relevant to robotic and human exploration objectives. Specifically, the LDPRL mission concept is responsive to Goal 6g (Study behavior of granular media in the lunar environment) and Goal 7k (Understand lunar dust behavior, particularly dust dynamics) identified in the ARTEMIS III SDT Team Report [1].

Key Science Objectives

There are a multitude of varied science objectives relevant to the dust-plasma environment near the lunar surface, making it a prime subject for a multi-investigator research facility with exchangeable payload instruments. For the initial deployment of such a laboratory, we have selected four science objectives that are both impactful and readily achievable with limited hardware development:

- Characterize the near-surface plasma environment.
- Measure dust particle charge on/near the surface.
- Determine whether or not electrostatic lofting occurs naturally.
- Determine whether or not electrostatic levitation occurs.

In addition to its value from a fundamental plasma physics perspective, the first two objectives are foundational to efforts to model electrostatic dust motion. The latter two objectives seek to use modern technology to look for evidence of electrostatic dust motion, prior evidence of which remains inconclusive.

Payload Concepts

To address the science objectives described above, we suggest four payloads: (1) near surface lunar plasma probe, (2) lunar dust charge detector, (3) lunar dust transport monitor, and (4) lunar horizon glow observer. Figure 1 shows an artist's concept of the Lunar Dust Research Lab with the four initial instruments. Table 1 gives the predicted mass and power requirements and the estimated technology readiness level (TRL) of each payload. We will now discuss each payload. Additional details about the payload suite and TRL assessment can be found in [6].

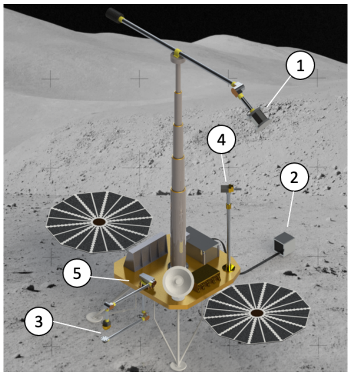

Figure 1: Lunar Dust and Plasma Research Lab (LDPRL) facility concept with initial investigation suite. Several instruments are on booms to prevent the presence of the facility from influencing the measurement. ① Langmuir probe, ② Dust charge detector, ③ Dust transport monitor, ④ Lunar horizon glow observer, ⑤ Central station with battery, communication, power, thermal, solar panel, and electronics hardware. (Image by D. Shelton)

Table 1: Estimated Payload Characteristics (excluding any required booms)

Instrument	Total Estimated Mass (kg)	Total Estimated Power (W)	TRL
Near Surface Lunar Plasma Probe	1.5	4	4
Lunar Dust Charge Detector	1.5	20-35	3
Lunar Dust Transport Monitor	2.5	20	4
Lunar Horizon Glow Observer	5	10	9

Near Surface Plasma Probe

Langmuir probes provide the simplest means for measuring plasma densities and temperatures in the expected parameter regime. We propose a cylindrical Langmuir probe with a sunshade to prevent photoemission of the probe itself. The proposed probe will have a collection area of 0.125 m^2 corresponding to 10 nA $< I_0 <$ 1 mA for $T_e = 10$ eV (I_0 is the reference electron current, T_e is electron temperature) and 1 $\text{cm}^{-3} < n_{e0} < 10^5$ cm^{-3} (n_{e0} is the electron number density at the surface). The cylinder radius is 0.1 m and length is 0.2 m. The cylinder axis of the probe would then be continuously adjusted to point towards the sun so the probe will always be in the shadow of the sunshade. The probe will be mounted on a 35 m long, retractable boom in order to characterize the plasma sheath as a function of height above the surface. The sheath is predicted to have a minimum in the electric potential $\sim$ 10 m above the surface [15]. The instrument platform will perturb the plasma environment via shadowing (which prevents photoemission of the shadowed surface) and electric charging of the platform itself. A boom is necessary to ensure that the probe can investigate the plasma environment that is not perturbed by the presence of the instrument platform.

Lunar Dust Charge Detector

We have considered two measurement techniques to investigate the charge of individual dust particles near the lunar surface.

The first technique considered is a high heritage technique to measure the induced currents in a wire configuration when particles fly by. This technique has been used already in space experiments [2] (e.g., the Electrostatic Lunar Dust Analyzer (ELDA) experiment). This technique would require particles to fly (either through natural motion or after being actively dropped) through a wire grid sensor. If a scoop or funnel is required to direct particles into the sensor, this will increase the payload mass. Alternatively, if the instrument passively waits for dust to be transported into the sensor (via e.g., electrostatic dust motion, or micrometeoroid impact), the influence of the instrument platform on the local plasma environment should be considered, as it may promote or reduce the dust flux to the instrument.

A second, less mature technique would be to directly measure the charge of the dust particle when it hits a surface and charges an ionCCD pixel sensor. This technology requires particles to impact the probe surface. This technique is predicted to reach a similar if not significantly better sensitivity than the one used in the ELDA experiment. However, it has been tested only for electrons, ions and charged molecules [5], not yet with dust particles.

Lunar Dust Transport Monitor

The Lunar Dust Transport Monitor consists of a camera observing an 8 cm diameter disk with 8-12 cm-scale material coupons in a ring. The camera will monitor dust accumulation on the individual material coupons by resolving mm-sized patterns of accumulation but not individual grains (which are likely micron-sized). An LED will also be necessary to illuminate the coupons prior to imaging. In the case of a transparent coupon, it may be advantageous to include the light source below the sample. The sample disk will rotate to position material coupons in the camera field of view on a daily cadence. We estimate that this system should be exposed to the lunar environment for approximately 3 mo in order to ensure detectable accumulation of dust particles. The sample disk should be deployed as close to the surface as possible to ensure that the flux of lofted particles is correctly detected (i.e., that none are 'missed' due to a peak altitude below the sample disk). The presence of the instrument platform will influence the local plasma environment. Thus, in order to monitor the natural transport of dust, it is necessary to deploy the sample disk on a horizontal boom at least 1 m in length. In order to re-initialize the experiment (i.e., clear any accumulated dust), the sample disk could be spun at a high rate. Using centrifugal forces to remove dust particles will also enable a measurement of the adhesion between the particles and the plate.

Horizon Glow Observer

First observed during the Surveyor era [14], Lunar Horizon Glow is a signature of scattered light observed tens of cm above the surface of the Moon after local sunset [16]. It has been hypothesized that lunar horizon glow could be caused by light forward scattering off of electrostatically levitating dust particles. However, recent reanalysis of Apollo observations indicate that the observed horizon glow may be entirely attributable to zodiacal light [3, 4]. Simulations suggest that electrostatic levitation should occur at altitudes of approximately 10 m above the suface [8]. We propose to look for the lunar horizon glow using two dedicated cameras: one focusing on high altitude (km-scale) particles and a second focusing on particles near 10 m. The camera looking for high altitude dust will be based on the star tracker on-board the Clementine spacecraft [13], while the other camera will be based on the Optical Navigation Camera Telescope on-board the Hayabusa2 spacecraft [11, 12, 18, 19].

Schedule and Cost

The major remaining technology developments required for the LDPRL baseline concept are: (i) demonstration of the plasma probe design in a relevant environment, (ii) further maturation of dust charge measurement technology, and (iii) maturing the LDPRL platform subsystems to enable measurements and survival during the lunar night. These technologies can be developed to TRL 5 prior to a Phase A start in 2024, with some development already funded by or proposed to the DALI program. We recommend BPS funding to complete the development of these technologies prior to the Phase A start. The development phases B-D durations are similar to recent NASA's in-situ planetary instruments on Mars 2020. And the durations of phases A/B/C/D will be roughly 0.5/1/1.5/1.5 year, respectively. We estimate the phases B-D cost approximately \$96M, including JPL's 35% reserve/uncertainty. We assume that the payload suite will be deployed by an ARTEMIS astronaut. The basis of estimate (BOE) for work breakdown structure (WBS) elements including management, systems engineering, mission assurance, science, and MOS/GDS is from the last 10 years of flown flight projects data. NASA Instrument Cost Model (NICM) tool is used to estimate the cost of instrument payloads with similar engineering complexity, mass, and power. The central station and I&T cost are based on the historical dollar/mass for planetary missions at JPL. The cost is rounded to nearest \$5M, or up to nearest \$1M if the estimation is less than \$5M. *The cost and schedule information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.*

Table 2: ROM cost estimation

WBS	Cost (\$M)
01 Project Management	3
02 Project Systems Engineering	3
03 Safety and Mission Assurance	3
04 Science	4
05 Payload	43
05.01 Payload Management	2
05.02 Payload Systems Engineering	2
05.03 Plasma Lunar Surface Probe (PLUS-probe)	12
05.04 Lunar Dust Charging Instrument (LDCI)	7
05.05 Lunar Dust Lofting/Transport Instrument (LDTI)	10
05.06 Lunar Horizon Glow Probe (LHGP)	10
06 Central Station + project I&T	17
07 MOS/GDS	7
Subtotal/(FY22\$)	80 / (73)
Reserves/Uncertainty	35%
Total (Phases B-D)	108

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References

[1] Artemis science definition team report. Technical Report NASA/SP-20205009602, NASA, 2020.

[2] N. Duncan, Z. Sternovsky, E. Gruen, S. Auer, M. Horanyi, K. Drake, J. Xie, G. Lawrence, D. Hansen, and H. Le. The Electrostatic Lunar Dust Analyzer (ELDA) for the detection and trajectory measurement of slow-moving particles from the lunar surface. *Planetary and Space Science*, 2011.

[3] David A. Glenar, Timothy J. Stubbs, James E. McCoy, and Richard R. Vondrak. A reanalysis of the Apollo light scattering observations, and implications for lunar exospheric dust. *Planetary and Space Science*, 59(14):1695–1707, 2011.

[4] David A. Glenar, Timothy J. Stubbs, Joseph M. Hahn, and Yongli Wang. Search for a high-altitude lunar dust exosphere using Clementine navigational star tracker measurements. *Journal of Geophysical Research: Planets*, 119:2548–2567, 2014.

[5] O. Hadjar, G. Johnson, J. Laskin, G. Kibelka, S. Shill, K. Kuhn, C. Cameron, and S. Kassan. IonCCD for direct position-sensitive charged-particle detection: from electrons and kev ions to hyperthermal biomolecular ions. *J. Am. Soc. Mass Spectrom.*, 2011.

[6] C. Hartzell, P. Bellan, D. Bodewits, G.L. Delzanno, et al. Payload recommendations for a multi-uswer facility to investigate dust-plasma interactions and dust remediation technologies on the moon. URL `https://umd.box.com/s/66993q662ln81j6de9booleordb49kfs`.

[7] C.M. Hartzell. Dynamics of 2D electrostatic dust levitation at asteroids. *Icarus*, 333: 234–242, 2019.

[8] C.M. Hartzell and D.J. Scheeres. Dynamics of levitating dust particles near asteroids and the moon. *Journal of Geophysical Research: Planets*, 118:116–125, 2013.

[9] C.M. Hartzell, X. Wang, D.J. Scheeres, and M. Horányi. Experimental demonstration of the role of cohesion in electrostatic dust lofting. *Geophysical Research Letters*, 40: 1038–1042, 2013.

[10] M. Horányi, G.E. Morfill, and T.E. Cravens. Spokes in saturn's b ring: Could lightning be the cause? *IEEE Transactions on Plasma Science*, 38(4):874–879, 2010. doi: 10.1109/TPS.2009.2034455.

[11] S. Kameda, H. Suzuki, Y. Cho, et al. Detectability of hydrous minerals using ONC-T camera onboard the Hayabusa2 spacecraft. *Advances in Space Research*, 56:1,519–1,524, 2015. doi: 10.1016/j.asr.2015.06.037.

[12] S. Kameda, H. Suzuki, T. Takamatsu, et al. Preflight Calibration Test Results for Optical Navigation Camera Telescope (ONC-T) Onboard the Hayabusa2 Spacecraft. *Space Science Review*, 208:17–31, 2017. doi: 10.1007/s11214-015-0227-y.

[13] Joseph F. Kordas, Isabella T. Lewis, Robert E. Priest, W. Travis White III, Darron P. Nielsen, Hye-Sook Park, Bruce A. Wilson, Michael J. Shannon, Arno G. Ledebuhr, and Lyn D. Pleasance. UV/visible camera for the Clementine mission. In Pierre Y. Bely and James B. Breckinridge, editors, *Space Telescopes and Instruments*, volume 2478, pages 175 – 186. International Society for Optics and Photonics, SPIE, 1995. doi: 10.1117/12.210943. URL `https://doi.org/10.1117/12.210943`.

[14] J. E. McCoy and D. R. Criswell. Evidence for a high altitude distribution of lunar dust. Proceedings of the Fifth Lunar Conference (Supplement 5, Geochimica et Cosmochimica Acta), pages 2991–3005, 1974.

[15] Tore Nitter, Ove Havnes, and Frank Melandsø. Levitation and dynamics of charged dust in the photoelectron sheath above surfaces in space. *Journal of Geophysical Research*, 103:6605–6620, 1998.

[16] J. J. Rennilson and David R. Criswell. Surveyor observations of lunar horizon-glow. *The Moon*, 10:121–142, 1974.

[17] J. Schwan, X. Wang, H.-W. Hsu, E. Grun, and M. Horányi. The charge state of electrostatically transported dust on regolith surfaces. *Geophysical Research Letters*, 44: 2017GL072909, 2017.

[18] H. Suzuki, M. Yamada, T. Kouyama, et al. Initial inflight calibration for Hayabusa2 optical navigation camera (ONC) for science observations of asteroid Ryugu. *Icarus*, 300:341–359, 2018. doi: 10.1016/j.icarus.2017.09.011.

[19] E. Tatsumi, T. Kouyama, H. Suzuki, et al. Updated inflight calibration of Hayabusa2's optical navigation camera (ONC) for scientific observations during the cruise phase. *Icarus*, 325:153–195. doi: 10.1016/j.icarus.2019.01.015.

[20] X. Wang, M. Horányi, and S. Robertson. Experiments on dust transport in plasma to investigate the origin of the lunar horizon glow. *Journal of Geophysical Research*, 114: A05103, May 2009.

[21] X. Wang, J. Schwan, H.-W. Hsu, E. Grun, and M. Horányi. Dust charging and transport on airless planetary bodies. *Geophysical Research Letters*, 43:6103–6110, 2016.

[22] Qi Yan, Xiaoping Zhang, Lianghai Xie, Dawei Guo, et al. Weak dust activity near a geologically young surface revealed by change'e-3 mission. *Geophysical Research Letters*, 46:9405–9413, 2019.