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Electrostatic Dust Transport and Its Effect on Human Exploration on the Surface of the Moon

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Primary Author:
Xu Wang
University of Colorado – Boulder
Phone: 303-217-3699
Email: xu.wang@colorado.edu

Co-Authors:
Donald Barker, Jacobs Technology Inc.
David T. Blewett, Johns Hopkins University – Applied Physics Laboratory
Rhushik Chandrachud, Mumbai University
Jan Deca, University of Colorado – Boulder
Gian Luca Delzanno, Los Alamos National Laboratory
Ian Garrick-Bethell, University of California, Santa Cruz
Amara Graps, Planetary Science Institute
Daoru Han, Missouri University of Science and Technology
Christine Hartzell, University of Maryland
Mihaly Horányi, University of Colorado – Boulder
Hsing-Wen Hsu, University of Colorado – Boulder
Devanshu Jha, MVJ College of Engineering
Akos Kereszturi, CSFK
Georgiana Kramer, Planetary Science Institute
Lorin Matthews, Baylor University
Joseph Wang, University of Southern California

Summary

Electrostatic dust charging and subsequent transport on the lunar surface due to direct exposure to the solar wind plasma and solar radiation is a more than five-decade-old problem. Dust activity has been suggested as an explanation for several lunar surface and near surface observations from the beginning of the Apollo era. Beyond the Moon, related observations indicate that this electrostatic process may be a universal phenomenon on airless bodies across the solar system. Recent laboratory studies have made important breakthroughs in understanding the fundamentals of dust charging, mobilization and lofting mechanisms. In-situ measurements on the lunar surface are needed to determine the ground truth of this fundamental physical process and ultimately solve this longstanding problem. This study well aligns with the scopes of the Biological and Physical Sciences (BPS) Division and has great implication for the surface evolution of airless bodies, and dust mitigation for human activities on the lunar surface. We therefore recommend the study of electrostatic dust charging and transport to be a priority of the BPS in the next decade.

1. Significance

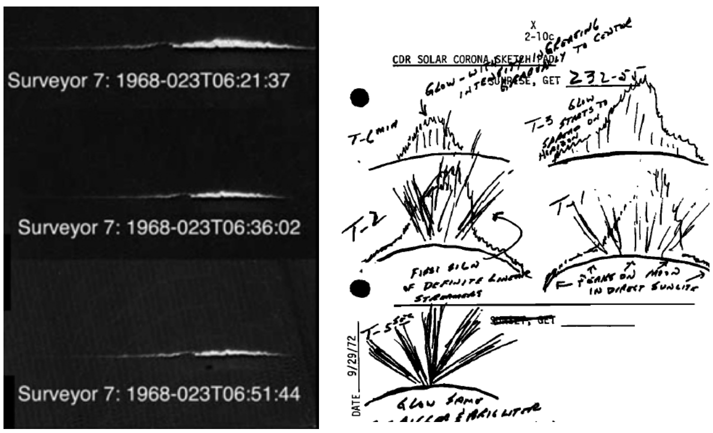

Fig. 1 *Left*: Lunar Horizon Glow images [Colwell et al., 2007]; *Right*: Sketches by the Apollo 17 astronaut E. A. Cernan, showing a global-scale horizon glow (appears as a shoulder on the corona and zodiacal light in the central bulge) and high-altitude streamers [Zook and McCoy, 1991].

The regolith of the Moon is directly exposed to the solar wind plasma and solar UV radiation, causing dust particles on the regolith to be charged. It has long been hypothesized that the charged dust particles may become mobilized, lofted, and transported by electrostatic forces. Several observations on the Moon have been thought to be related to this fundamental physical process. **Increased attention has been attracted from broad science communities because this electrostatic process may play a role in shaping the physical properties of the lunar surface, and may pose risks for future human exploration and settlement on the lunar surface.**

The first evidence of electrostatic dust transport was the Lunar Horizon Glow (LHG), which was inferred from observations recorded by the TV cameras onboard several Surveyor lunar landers in late 1960s, an example from Surveyor 7 is shown in Fig. 1 (left). The bright glow about 30 cm above the lunar surface was believed to be due to sunlight being forward scattered by a cloud of dust particles (~10 µm in diameter) that were electrostatically levitated above the surface at lunar terminator [Criswell, 1973; Colwell et al., 2007]. This lofting height is shown to be consistent with a recent observation by the Chang'e-3 rover, which identifies a layer of fine dust deposits on lunar rocks up to ~28 cm high [Yan et al., 2019].

Later, the Lunar Ejecta and Meteorites Experiment (LEAM), deployed on the lunar surface, registered up to hundreds of hits per day of low-speed (<100 m/s) dust particles, mostly during terminator crossings, as opposed to a few hits per day of hypervelocity (1 – 25 km/s) cosmic dust particles [Berg et al., 1976]. However, later work analyzing different LEAM datasets [Grün and

Horányi, 2013] found no significant rate enhancement associated with the terminator crossing. Questions regarding instrument operations confounding data results have also been forwarded [O'Brien, 2018]. Additionally, a large-scale horizon glow and high-altitude streamers illustrated in sketches by Apollo astronauts (Fig. 1, right) were suggested to be attributed to submicron sized (~0.1 μm in radius) dust particles lofted to 10-100 km altitudes through electrostatic mechanisms [Zook and McCoy, 1991]. Though the Apollo remote-sensing observations also indicate an excessive brightness in the zodiacal light [Glenar et al., 2011], such a dense dust population was neither indicated from the remote sensing observations by Clementine [Glenar et al., 2014] and LRO/LAMP [Feldman et al., 2014], nor indicated from the orbital dust measurements by LADEE/LDEX [Szalay and Horányi, 2015]. **In-situ measurements on the lunar surface are needed to unambiguously verify the occurrence and the extent of electrostatically lofted dust from the surface.**

Fig. 2 LRO image of the Reiner Gamma Swirl.

Swirl-shaped, high-albedo markings on the lunar surface (Fig. 2), the so-called lunar swirls, have recently attracted great attention because they represent locations with high science values in plasma physics, planetary science, and human exploration [Blewett et al., 2011; Kramer et al., 2011]. Electrostatic dust transport is one of the hypotheses for the origin of these swirls. It has been suggested that electrostatically lofted dust particles may be sorted by electric fields created as a result of solar wind plasma interactions with lunar magnetic anomalies at the location of the swirls, forming high-albedo patterns due to the increased relative brightness of fine dust particles [Garrick-Bethell et al., 2011]. Such dust transport has recently been confirmed in the lab using small scale models of the magnetic fields found at the Reiner Gamma and Airy formations [Dropmann et al., 2016]. Additionally, the polar ice occurrence might be also influenced by lofting dust, if the H_2O adsorbed by such grains levitating around the terminator, and at polar depressions in which the terminator almost constantly presents.

Beyond the Moon, the dust ponds on asteroid Eros [Robinson et al., 2001; Colwell et al., 2005], the 'spokes' in Saturn's rings [Smith et al., 1981; Morfill et al., 1983], and the highly smooth surface of Saturn's icy moon Atlas [Hirata and Miyamoto, 2012] are all examples related to electrostatic dust transport. **Measuring electrostatic dust transport on the Moon will advance our understanding of this process and its role in surface processing on all airless bodies in the solar system**.

Mobilized dust due to natural mechanisms and/or human activity poses potential risks to future surface habitation and sustainability. The charging properties of the dust particles increase the difficulty to predict their behavior. As reported from the Apollo missions, dust particles can readily stick to all surfaces. A number of problems during the Apollo missions arose from dust loading [Afshar-Mohajer et al., 2015], including damage to spacesuits due to the abrasiveness of lunar dust, degradation of radiators, issues with thermal control systems and retroreflectors, and interference with hatch seals and Extravehicular Activity (EVA) systems. In addition, dust brought back to living quarters could lead to serious health risks if inhaled by astronauts for long durations. Dust mitigation has been recognized by the Lunar Surface Innovation Consortium (LSIC) as one of the major technical challenges for future human and robotic exploration on the lunar surface, especially for the long-term human presence. **Behavior of charged dust needs to be well-**

characterized in order to define appropriate operations, design, testing, and dust mitigation strategies and methods for lunar surface exploration.

This study addresses 1) a top science goal in the Lunar SCEM 2007 report: *Science Goal 8b - Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy*; 2) Objective 7k in the Artemis III SDT report: *Understand lunar dust behavior, particularly dust dynamics*; 3) Strategic Objective 2.2 in the NASA 2018 Strategic Plan: *Conduct human exploration in Deep Space, including to the surface of the Moon*; and 4) Global Exploration Roadmap: *Enable sustained living/working around and on the Moon*.

2. Current Understanding and Outstanding Questions

2.1 Current Understanding of dust charging and lofting mechanisms

Motivated by the observations described above, electrostatic dust charging and lofting has been explored through laboratory experiments, theoretical studies, and computer simulations over the past years. However, previous charging models, including the shared charge model [Flanagan and Goree, 2006] and the charge fluctuation theory [Sheridan and Hayes, 2011], cannot fully explain how dust can obtain enough charge to be lofted on the lunar surface. Modeling studies of dust dynamics above the surface of the Moon and other airless bodies could only be based on assumptions of initial lofting conditions such as initial charge and launch velocity.

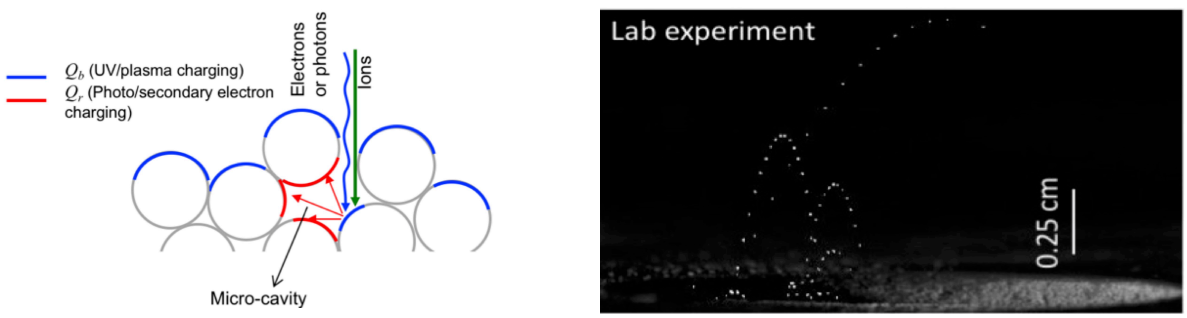

Fig. 3 *Left*: Patched Charge Model for regolith dust particles [Wang et al., 2016]; and *Right*: Trajectories of electrostatically lofted dust particles [Wang et al., 2016].

Recent laboratory experiments have revolutionized our understanding of dust charging and lofting. A new Patched Charge Model (Fig. 3, left) developed based on advanced laboratory experiments (Fig. 3, right) [Wang et al., 2016] has shifted our view from the charging process on the regolith surface to *microstructures* within the regolith. It is shown that the emission and re-absorption of photoelectrons and/or secondary electrons inside microcavities between dust particles can result in a buildup of large, negative charges on the surrounding particles, such that the subsequent strong repulsive forces between these particles cause their lofting or mobilization. A computer simulation [Zimmerman et al., 2016] has since also shown significant charging enhancement at a grain-scale level.

Since then, more laboratory experiments have produced results in support of the Patched Charge Model and provided new insights into the characteristics of dust charging and lofting, including the initial charge [Schwan et al., 2017] and launch velocity [Orger et al., 2019; Carroll et al., 2019], the lofting rate [Hood et al., 2018], and the size distribution [Hood et al., 2022]. An extended Patched Charge Model was recently developed to explain the laboratory observations of dust mobilization in the presence of a magnetic field [Yeo et al., 2021]. It is shown that the charging and lofting process depends on the ambient plasma conditions and the regolith and dust properties, which include regolith compaction, dust size, shape and composition, and subsequent photo/secondary electron emission and inter-particle cohesion [Hartzell and Scheeres, 2011; Hartzell et al., 2013; Wang et al., 2016; Dove et al., 2018].

2.2 Outstanding Science Questions

Though the laboratory experiments have greatly advanced our knowledge of electrostatic dust charging and lofting, they do not fully represent conditions on the surface of the Moon, including regolith cleanliness, compactness and composition, solar wind and UV radiation conditions and variability, near-surface plasma and field environments, and lunar gravity. The outstanding questions remaining include:

- **What is the charge, velocity, mass (size), and flux of electrostatically lofted dust particles on the lunar surface?**
- **How does dust charging and lofting change as a function of lunar local time?**
- **How does dust charging and lofting vary across different locations, including lunar terminator, magnetic anomaly, and permanently shadowed regions?**

3. Recommendations on future studies in the next decade

The Moon is a great platform for in-situ experiments of electrostatic dust transport, provided by its relatively easy access by landed missions, including both Commercial Lunar Payload Services (CLPS) and NASA's Artemis program. Dedicated in-situ dust instruments are needed to measure the charge, velocity, mass (size), and flux of lofted dust in order to determine the ground truth of electrostatic dust transport on the lunar surface. Combined with plasma instruments (e.g., Langmuir probes), full dynamics of lofted dust can be understood. These measurements are recommended to be taken over different locations and local times to examine and compare how dust activities vary with different surface and plasma conditions. Additionally, remote sensing measurements (e.g., cameras) are recommended to investigate dust at higher altitudes over a global scale.

Measurements are also recommended to investigate the effects of added human systems and activities on behavior of charged dust, as they can alter the regolith and surrounding plasma conditions. These will help develop the deployment and operation strategies, design of any payloads and hardware that interact with the lunar surface and In-Situ Resource Utilization (ISRU) activities, and appropriate dust mitigation methods, especially methods based on electrodynamics.

Electrostatic dust transport as a fundamental physical process falls in the scopes of the BPS Division and is suggested to be a high priority study in the next decade. This study also creates great collaborations between divisions within the SMD and between different directorates like STMD, ESDMD and SOMD.

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