Dust-Plasma Science Investigations and their Relevance to Lunar Exploration

Authors:
Christine Hartzell, University of Maryland
Dennis Bodewits, Auburn University
Gian Luca Delzanno, Los Alamos National Laboratory
Inseob Hahn, Jet Propulsion Laboratory
Daoru Han, Missouri Science and Technology
Masatoshi Hirabayashi, Auburn University
Truell Hyde, Baylor University
Uwe Konopka, Auburn University
Kausik Mukhopadhyay, University of Central Florida
Xu Wang, University of Colorado at Boulder

1. Abstract

With the renewed emphasis on exploration (both human and robotic) of the Moon, the challenge posed by lunar dust has come to the forefront. The behavior of dust on the lunar surface defies our intuition because it's physical characteristics (size, shape, and dominant particle-particle interactions) are not shaped by the ubiquitous forces of water and gravity that dominate the terrestrial environment. Especially foreign is the interaction of lunar dust particles with the near-surface plasma environment, which has no analog in the terrestrial environment. Investigations of the fundamentals of dust-plasma interactions are needed for future dust mitigation technology development. Additionally, exploration vehicles and activities will modify the near-surface plasma environment and vehicle charging may be dominated by the near-surface plasma. Thus, the plasma environment, dust behavior and spacecraft activities form an interdependent system (see Figure 1) and an improved understanding of dust-plasma interactions will thus inform the spacecraft design process. Additional investigations of spacecraft-plasma interactions and spacecraft-dust interactions can likely be carried out using the same instrumentation as that required for dust-plasma investigations. Thus, we suggest that dust-plasma interactions be a priority of the Biological and Physical Sciences Division in the next decade.

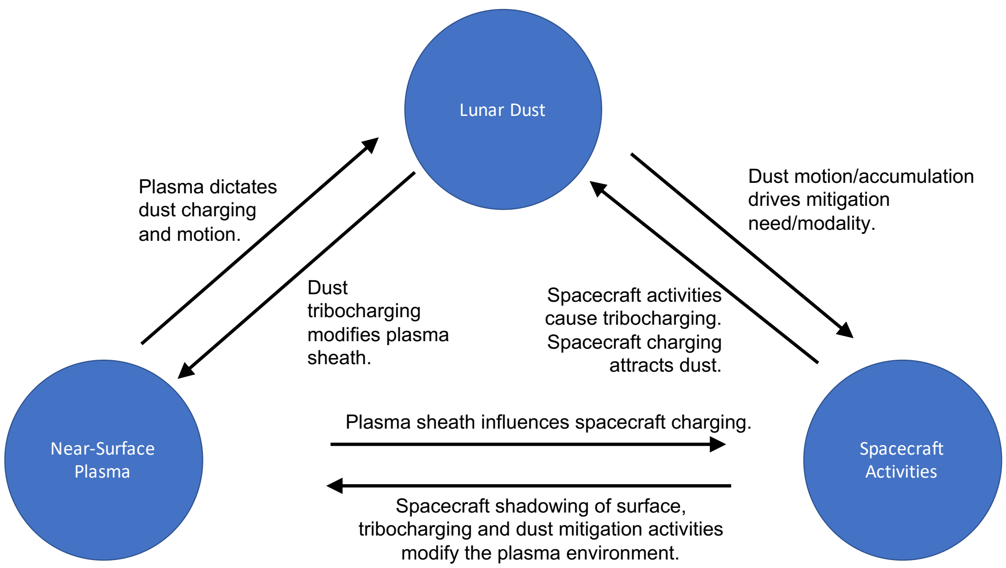

Figure 1: The plasma environment, dust behavior and spacecraft activites form an interdependent. Investigations of dust-plasma interactions reduce the uncertainty in one link of this cycle.

2. Dust-Plasma Interactions

Because the Moon lacks an appreciable atmosphere and global magnetic field, the dust on the surface of the Moon interacts directly with the solar wind plasma. The solar wind plasma and the solar UV radiation cause the dust particles on the lunar surface to have non-zero electric charge (even when the dust is in its natural state, undisturbed by exploration activities). Because the surface is charged, a plasma sheath is formed above the lunar surface, which is a region where the number densities of electrons and ions are not equal.

The resulting spatial variation of the plasma density produces an electric field. The possible repulsion between charged regolith particles has been hypothesized to cause dust particles to detach from the lunar surface (called electrostatic lofting) [9, 12, 13, 11, 5]. Additionally, particles that have detached from the lunar surface (via e.g., electrostatic lofting, spacecraft activities, or micrometeoroid bombardment) have also been hypothesized to hover above the surface (called electrostatic levitation) [4, 6, 10] when the gravity and electrostatic forces are balanced.

There remain several fundamental questions of dust-plasma interactions that are poorly understood:

- What is the charge on a dust particle on a solid surface in a plasma?
- What is the charge on a dust particle in a bed of other particles in a plasma (e.g. a single regolith particle on the lunar surface)?
- How does dust charging on a surface or in a plasma sheath depend on the particle's chemical composition and shape?

The charge on dust particles (especially dielectric particles) on a surface in a plasma remains challenging to both predict and measure. Recent work has made significant progress in predicting particle charge by considering the exchange of electrons between neighboring grains [12, 13]. As grain charge is a key input to simulations of grain motion and behavior, in situ measurements of this quantity are very important. Additionally, all models to date assume spherical grains of a single uniform chemical composition. The sensitivity of grain charge to particle shape and chemistry remains unknown.

There are several additional questions specific to the lunar surface that have implications for both science and exploration:

- How does the plasma density near the lunar surface (on the scale of meters) vary with altitude, location on the surface and time of day?
- Does electrostatic lofting occur on the Moon?
- Does electrostatic levitation occur on the Moon?

As with particle charge, plasma density variation is a key input to models of the near surface environment on the Moon. Existing models of the near-surface plasma environment (e.g. Nitter et al. [8]) require in situ measurements for proper calibration and validation.

While we traditionally think of the plasma environment dictating the charge on lunar dust particles, if lunar dust is charged via exploration activities, then the plasma environment will be modified (at least temporarily) until the particles return to their equilibrium charge state. Exploration activities that cause lunar dust to move (e.g. rolling wheels, roving astronauts, drilling, digging and lander plume impingement) will cause triboelectric charging [7], which is charge exchange that occurs when two surfaces collide or rub against each other. In the terrestrial environment, tribocharging is called 'static electricity' and is usually quickly neutralized by the water in the atmosphere. On the lunar surface, tribocharged spacecraft and regolith will be neutralized by the plasma sheath over a much longer timescale, thus leading to a modified plasma sheath prior to neutralization.

The final two questions address the feasibility of electrostatic lofting and levitation on the Moon. While prior observations (e.g., lunar horizion glow [9, 1]) have been explained by these phenomena, there is currently no conclusive, direct evidence of these phenomena. Additionally, electrostatic lofting and levitation may pose a contamination risk to surface spacecraft if the flux of dust particles onto spacecraft is large. We suggest that modern instruments, designed specifically to detect electrostatic lofting and levitation be landed on the lunar surface, in order to understand phenomena that may be important for the evolution of multiple solar system bodies as well as the design of exploration systems.

3. Dust-Spacecraft Interactions (relevant to the plasma environment)

Dust may accumulate on spacecraft after being mobilized by lander plumes or other exploration activities, and may be accelerated towards the spacecraft by electrostatic forces. Additionally, dust may accumulate on spacecraft after being electrostatically lofted. The needed frequency of dust removal/mitigation operations will be dictated by the flux of dust on the spacecraft. Thus, it is necessary to understand the flux of electrostatically lofted dust as well as the size of deposited dust particles in order to plan efficient mitigation operations. Additionally, many current mitigation technologies rely on electrostatic forces in particle removal [2, 3]. Thus, it is necessary to understand the charge on the particles in order to properly predict the efficacy of these technologies.

Spacecraft activities also influence the charge of dust particles. As mentioned previously, exploration activities are likely to produce tribocharging, thus changing the electrical charge of regolith particles. Additionally, the non-zero electrical charge of the spacecraft can cause an electrostatic force on particles (either repulsion or attraction), although this interaction is mediated (and will be partially shielded) by the near surface plasma.

4. Plasma-Spacecraft Interactions

The near surface plasma environment will influence the equilibrium charge on the spacecraft, which will influence the attraction or repulsion of dust to/from the spacecraft. In turn, the spacecraft will influence the local environment via several effects. Firstly, the spacecraft will cast a shadow on the lunar surface. This shadow will cause a small plasma wake to form, characterized by the dearth of ions and photoelectrons in the shadowed region. This modification of the plasma and shadowing of regolith from the solar UV will change the charging of the lunar dust. As discussed previously, exploration activities will also cause triboelectric charging of the regolith, which will in turn cause modification of the plasma sheath, as it responds to return the surface to equilibrium.

Mitigation technologies that rely on electrostatic forces to provide cleaning will also modify the local plasma environment. The electrodynamic dust shield developed at NASA-Kennedy uses a traveling wave moving across electrodes embedded beneath a surface to clear dust particles [2]. Other techniques involve irradiating a dust covered surface using an electron beam [3]. Any modification of the surface potential or the charge of regolith grains induced by mitigation efforts will modify the local plasma environment.

5. Conclusion

Understanding the fundamental physics of dust-plasma interactions on the lunar surface (especially particle charging) will influence our understanding of the evolution of the surface of airless planetary bodies, and inform predictions of a potential hazard to long-duration lunar missions (e.g. through modified spacecraft thermal properties or clouded optics). Additionally, it is important that we study dust, plasma and spacecraft as an interconnected system, with an emphasis on uncovering the interplay between these components. Investigations of the fundamental physics of dust-plasma interactions are timely and well suited to future NASA Biological and Physical Sciences missions or instruments to the lunar surface.

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