51st International Conference on Environmental Systems
10-14 July 2022, Saint Paul, MN

ICES-2022-214

Electrostatic charging of the lunar surface

James R Phillips III,[1] Charles R. Buhler,[2] Michael R. Johansen,[3] and Carlos I. Calle[2]
Electrostatics and Surface Physics Laboratory, NASA Kennedy Space Center, FL 32899, USA

Adrienne R. Dove[4]
Center for Microgravity Research, University of Central Florida, Orlando, FL 32816, USA

Lunar regolith dust particles accumulate charge and interact electrostatically with rover wheels, astronaut boots, and equipment. We have developed instrumentation for in situ measurements of the electrostatic charge developed by the interactions of lunar regolith dust with the space-rated materials on these devices. This instrument is also capable of measuring the distribution of electric fields on or near the lunar surface and the ion currents present near the lunar surface. We also report on our efforts to characterize the charging behavior of lunar dust in low gravity environments. This behavior is nonintuitive due to complex interactions between individual dust grains. We are developing an experiment to study this interaction in a microgravity vacuum environment. Better understanding of this interaction will allow for improved dust mitigation on the lunar surface.

Nomenclature

ARTEMIS = Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun
ERIE = Electrostatic Regolith Interaction Experiment
GCR = Galactic Cosmic Rays
I = current
LADEE = Lunar Atmosphere and Dust Environment Explorer
LEAM = Lunar Ejecta and Meteorites
MECA = Mars Environmental Capability Assessment
MSI = multi-sensor instrument
R = resistance
V = voltage
WES = Wheel Electrostatic Spectrometer

I. Introduction

THE lunar surface interacts directly with the solar wind, cosmic rays, and the solar ultraviolet radiation. Knowledge of the complex electrical environment that this interaction produces is essential from a scientific perspective as well as for hazard mitigation for lunar human missions. A full understanding of the lunar electrical environment requires measurements *in situ*.

We have developed a Multi-Sensor Instrument (MSI) for *in situ* measurements of the fundamental properties of the lunar electrostatic environment. This instrument measures the distribution of electric fields on and near the lunar surface, the electrostatic charge developed by interactions of several polymers with the lunar regolith, and the ion currents present near the lunar surface. The multi-sensor instrument is designed to be attached to a lander's robotic arm. This configuration will allow the electrometer sensors to contact the lunar soil and will also allow the electric field and ion sensors to take measurements as a function of distance from the surface.

In this paper, we describe what is known about the lunar electrostatic environment from direct measurements, simulations, and modeling. We then describe the MSI and provide experimental data with a prototype taken at high vacuum conditions.

---

[1] Research Scientist, NASA KSC Mail-code UB-G, Kennedy Space Center, FL 32899
[2] Senior Research Scientist, NASA KSC Mail-code UB-G, Kennedy Space Center, FL 32899
[3] Research Engineer, NASA KSC Mail-code UB-G, Kennedy Space Center, FL 32899
[4] Assistant Professor, University of Central Florida, 4000 Central Florida Blvd., Orlando, FL, 32816

II. The Lunar Electrostatic Environment

A. Electrostatic Charging of the Lunar Surface

Our current understanding of the complex lunar electrical environment is derived from a formalism that was initially developed by Manka[1] and completed by Halekas *et al.*[2] and by Farrell *et al.*,[3] with inputs from spacecraft data. This formalism is based on the law of conservation of electric charge: in equilibrium, the lunar surface will develop a charge so that the sum of the solar wind, cosmic rays, and UV current fluxes cancels out. Measurement of electron concentrations and temperatures for typical solar wind conditions with the electron reflectometer instrument on NASA's Lunar Prospector mission[2] showed that most of the contribution to electrostatic charging on the lunar surface is provided by just four currents: photoelectrons, solar wind electrons, solar wind ions, and secondary electrons.[4]

The magnitude and sign of the charge on the lunar surface is different for the sunlit and the nightside of the Moon.[5] On the sunlit side, the surface on the Moon develops a positive charge due to the photoelectrons from the under 200 nm ultraviolet radiation from the Sun and the solar X-rays. These photoelectrons form a sheath with a density of 10^3 to 10^4 electrons/cm^3 about 1 m above the daylight lunar surface that shields the surface from the plasma.[6] A small positive potential of about 5 V to 10 V balances the photoelectron and incident solar wind electron currents.[7]

On the nightside of the Moon, in the solar wind wake, the density of the charged particles from the solar wind is reduced considerably. In this reduced plasma environment, electrons gain kinetic energy and, being lighter than the ions, become the prevailing current. The dominant electron flux charges the lunar surface to potentials of about –50 V to –200 V.[8] However, these potentials can be in the hundreds of kilovolts when the Moon crosses the Earth's plasma. The Lunar Prospector spacecraft measured nightside surface potentials of –4.5 kV during periods of intense solar activity.[9] This plasma environment forms a sheath on the lunar nightside that reaches about 1 km from the surface.[10,11] A similar phenomenon at a smaller scale occurs on the dark side of craters in the polar regions. The surfaces of these dark areas are charged to several hundred volts.[12] A potential difference then develops across the boundary between the sunlit and dark sides of the Moon. This potential difference has been estimated to be of the order of about –40 V.[4,8]

B. Deep Dielectric Charging of the Lunar Surface due to Galactic Cosmic Rays

Interactions between incident Galactic Cosmic Rays (GCR) and the atoms in the lunar regolith produce secondary emissions from the lunar surface that are relatively small compared to the photoelectron and plasma electron currents. However, these smaller emissions are still important.

In addition, GCR can generate deep dielectric charging in the lunar soil at depths of about 1 m.[13] As a result, electrostatic discharges can occur in the regolith. A current project by Reka Winslow and collaborators is estimating the subsurface electric field strength and the possibility of dielectric breakdown in the lunar regolith.[13] They use a deep dielectric charging model developed by Jordan *et al.*[14] with data from NASA's Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission that measures the solar radiation incident on the lunar surface as the Moon moves in and out the Earth's magnetic field.

C. Triboelectric Charging on the Lunar Surface

Triboelectric charging develops when two surfaces make contact and separate from each other, exchanging electrons, ions, or charged particulates. Rover wheels or the soles of astronaut boots will be triboelectrically charged as they move along the lunar surface. The time it would take for this electrostatic charge to dissipate depends on the surrounding plasma environment.[15,16]

A rover is also exposed to all the current fluxes reaching the surface of the Moon, developing a charge that balances out the net sum of the fluxes. In the conductive photoelectron-dominated plasma region of the sunlit surface of the Moon, the triboelectric-generated charge that would develop on a rolling rover wheel should dissipate quickly. A study by Farrell *et al*. with the rubber tires on the wheels of the Modular Equipment Transporter and with the metallic tires on the Lunar Roving Vehicle used during the Apollo missions showed this to be the case.[17]

III. The Multi-Sensor Instrument

To increase our knowledge of the complex lunar electrostatic environment described in Section II, our MSI is designed to measure the electric field configuration near the lunar surface using an electric field sensor, the electrostatic interaction of the lunar regolith with typical flight materials using electrometer sensors, and the presence of ions using an ion gauge. This instrument was fully developed into a flight instrument for the Martian environment as part of Mars Environmental Capability Assessment (MECA) soil science suite for the Mars 2001 Surveyor Lander (cancelled) (Figure 1).[18] The new version will be assembled with the required upgrades for compatibility with the lunar environment.

Table 1. Polymers used for the triboelectric sensors span the triboelectric series[18]

No.	Material Name	Chemical Name	ε @ 1 MHz	Resistivity (ohm-cm)
TRI1	G10, FR4	Fiberglass Epoxy	4.7	7.8E15
TRI2	Lexan™	Polycarbonate	2.96	2E16
TRI3	Teflon™ PTFE	Polytetrafluoro ethylene	2.1	1E18
TRI4	Rulon J™	—	2.4	8.2E18
TRI5	Lucite™	Polymethyl-methacrylate	2.63	>5E16
	PMMA			>1E14

To achieve its purpose, the MSI is designed to be mounted on the heel of a lander's robotic arm scoop so that it can be rubbed against the lunar regolith. To measure the interaction between regolith and the typical flight insulating materials, the five polymers shown in Table 1 are placed over the electrometer sensors. These polymers span the triboelectric series, a classification indicating the tendency of a material to gain or lose electrons in contact with another material. The relative position of two materials in the series roughly determines which will be positively charged and which will be negatively charged when they are rubbed together.[19]

While the MSI makes contact with and later separates from the lunar surface, the five polymer disks capping the electrometer sensors exchange electrostatic charge with the lunar regolith. This electrostatic charge depends on the physical properties of the five polymers. As the robotic arm is raised or lowered, the electric field sensor and the ion gauge will measure changes in the electric field and will detect charged species near the lunar surface. While this setup was originally planned for deployment on the Martian surface, application to the lunar surface will be possible with minor modifications. Since the insulators span the triboelectric series, performance of the triboelectric sensors should be similar when applied to the lunar surface as compared to that of Mars. Differing initial conditions for charge on the regolith may necessitate tweaking the gains on the amplifiers to ensure the measured values stay within the range of the analog to digital converters. Along similar lines, the amplifier gains servicing the ion and electric field sensors may need tweaking to compensate for the expected difference in relative strengths of the ion currents and fields.

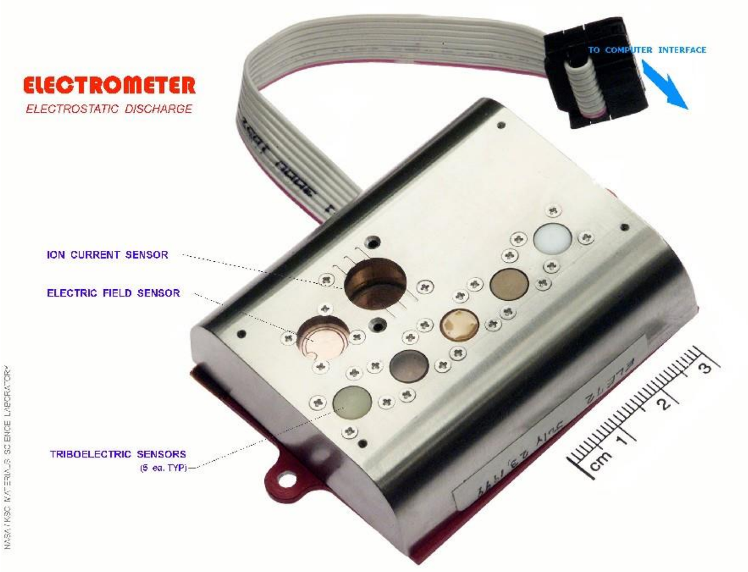

Figure 1. The MECA Electrometer

The MSI with its temperature sensor, the ion gauge, the electric field sensor, and the five triboelectric sensors inside a single titanium case has a total mass of about 160 grams and volume of 80 cm^3 (Figure 1). The triboelectric sensor consists of a ground ring, a guard ring, and a sensing pad. The inner concentric ring removes electric field edge effects while the outer ring acts as a ground. The selected polymer material is placed above this sensing pad and is exposed through the titanium enclosure to make direct contact with the lunar regolith. The electric field above the test material depends on the surface charge density and the geometry of the sensor. The maximum surface charge is 240 pC or 1.5×10^9 elementary charges. This charge is impressed on the sensing capacitor in the electrometer, generating a voltage that is amplified and then measured. On average, the triboelectric-sensor sensitivity is 1.8 kV/V and full-scale detection capability of 7.3 kV with a resolution of 3.5 V. The full-scale charge detection capability and resolution is 1800 ± 0.9 pC. The charge particle resolution is 5.5 million charges.[18]

As each polymer comes into contact with the lunar surface, an electrostatic charge exchange takes place (Figure 2).[20] As the surface of the sensor separates from the regolith, an increased electrostatic potential develops. Since the output of the sensor circuit is proportional to the charge on the insulator, a time sampling of the sensor indicates when both of these events occur.

The electric field sensor in the MSI is designed to measure electric field strength near the lunar surface and the ion gauge is designed to measure local ion currents. These sensors will also detect diurnal surface charging and plasma conditions. The full-scale ion gauge capability is 120 pA and the resolution is 60 fA. The ion gauge circuit is basically a current-to-voltage converter, as shown in Figure 3. In the actual circuit, the electrode is held at either a positive or a negative voltage. This causes negative or positive charges, respectively, to accelerate toward the electrode, thus producing the electric current that the circuit detects.

Figure 4 shows a typical experimental data run with the original MECA electrometer in which the regolith was kept at room temperature but under Martian atmospheric conditions. Initially, there is a background signal (~30 mV) before contact. The electrometer is placed onto the regolith and charge is exchanged between the polymer material and the regolith. As the electrometer is lifted from the regolith, charge separation occurs, producing a potential difference between the two surfaces.

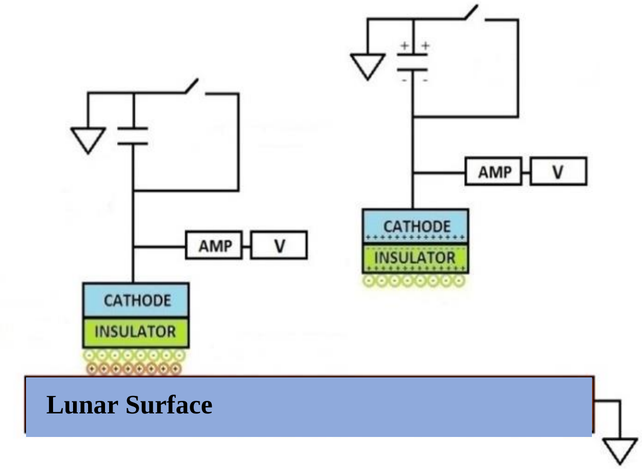

Figure 2. Simplified electronics diagram[20]

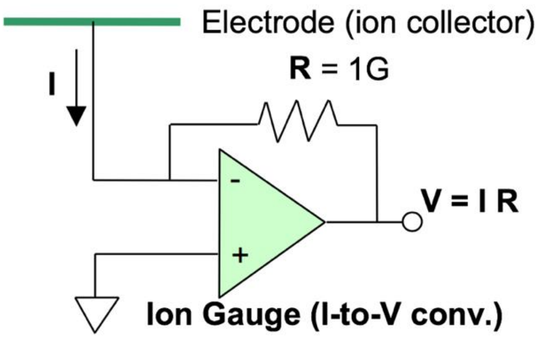

Figure 3. Ion gauge diagram[20]

When the electrometer is placed back on the regolith (at 31 seconds in Figure 4), the equal and opposite charges are brought back together, reducing the potential. The remaining potential detected is likely due to charged particles adhering to the surface or to charges that leaked into the bulk of the insulator. From there on, the potential increases and decreases at roughly the same values with each separation and contact.

Figure 4 indicates that the five polymers acquire different electrostatic charges when in contact with the Martian regolith. These electrostatic responses can be arranged in a triboelectric series table according to the amount of charge transferred.[21] Measurements obtained by the MSI will place the lunar regolith in these tables. Since other widely used polymer materials are classified in these tables, the magnitude and sign of the charge that they may acquire if they were to be placed in contact with the regolith can be predicted. This information will allow mission designers to predict if the proposed material will accumulate dust. Our planned laboratory experiments will provide direct experimental data to validate these predictions.

Several configurations of the triboelectric sensors included in the MSI have been examined for different applications. The Wheel Electrostatic Spectrometer (WES)[20,22] employs sensors spaced along the perimeter of a rover wheel (Figure 5) to characterize triboelectric properties of regolith contacted as the wheel rotates. The Electrostatic Regolith Interaction Experiment (ERIE) integrates an array of sensors into a sliding door (Figure 6) that provides dust containment for experiments performed on microgravity flights. Previous flight experiments, such as the COLLisions Into Dust Experiment (COLLIDE),[23] study the mechanics of large bodies colliding into regolith simulant dust beds under microgravity. These experiments showed grains ejecting from the bed when the retaining door was retracted. One hypothesis to explain this behavior is that the dust grains have acquired electric charge through agitation during launch and repel one another. This repulsion is typically overcome by gravity on the surface of the Earth, but in the free fall microgravity environment, new mechanics are observed. To test this hypothesis, ERIE was developed to measure the charges on the bulk and individual dust grains, alongside complementary visual observations of the grains.

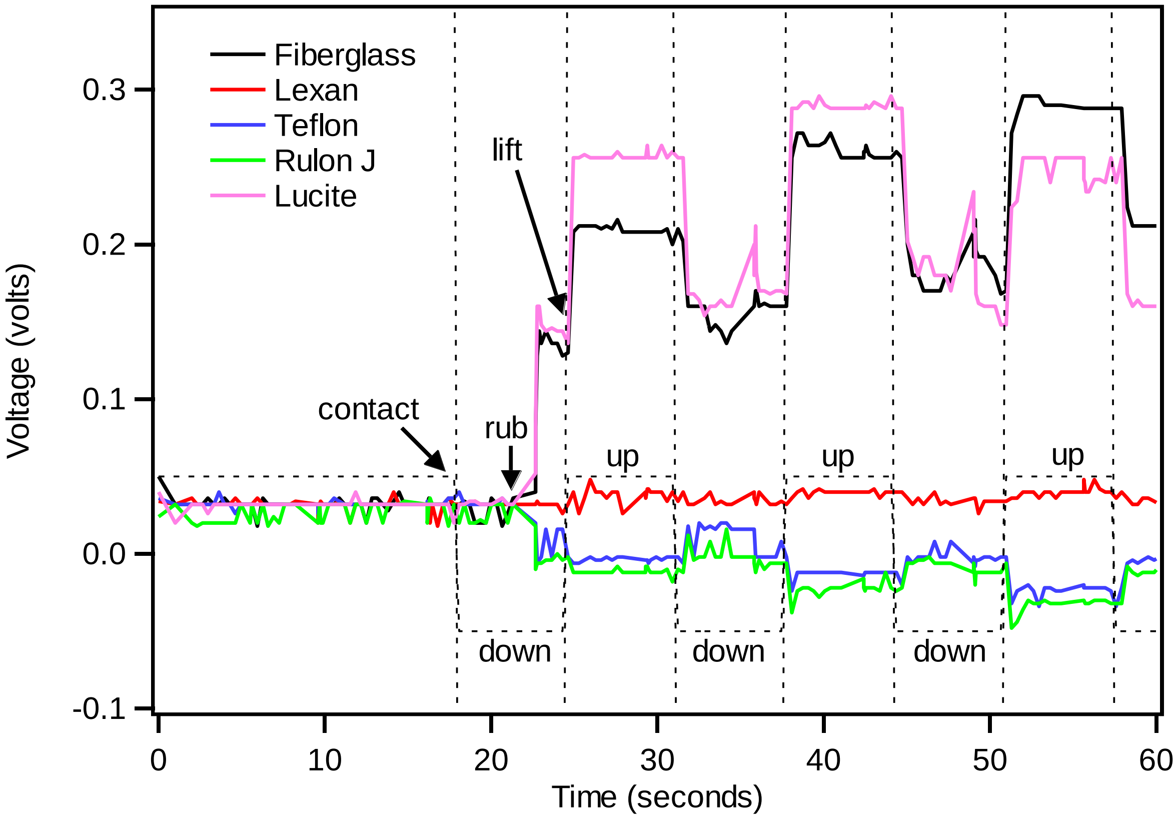

Figure 4. A typical experiment in which the MECA electrometer is rubbed repeatedly onto the JSC Mars-1 simulant at Martian atmospheric conditions at room temperature.[20]

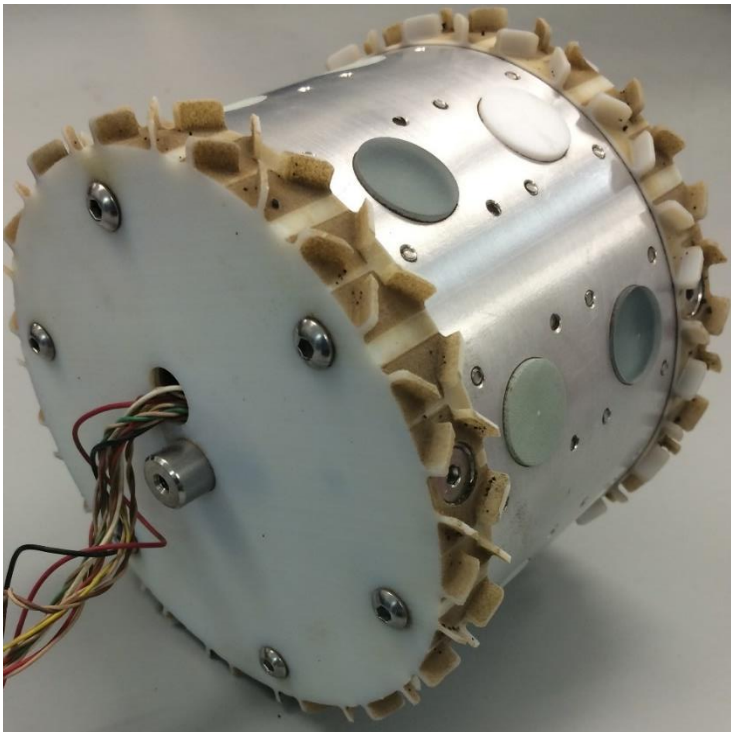

Figure 5. Wheel Electrostatic Spectrometer (WES) prototype with triboelectric sensors spaced along circumference

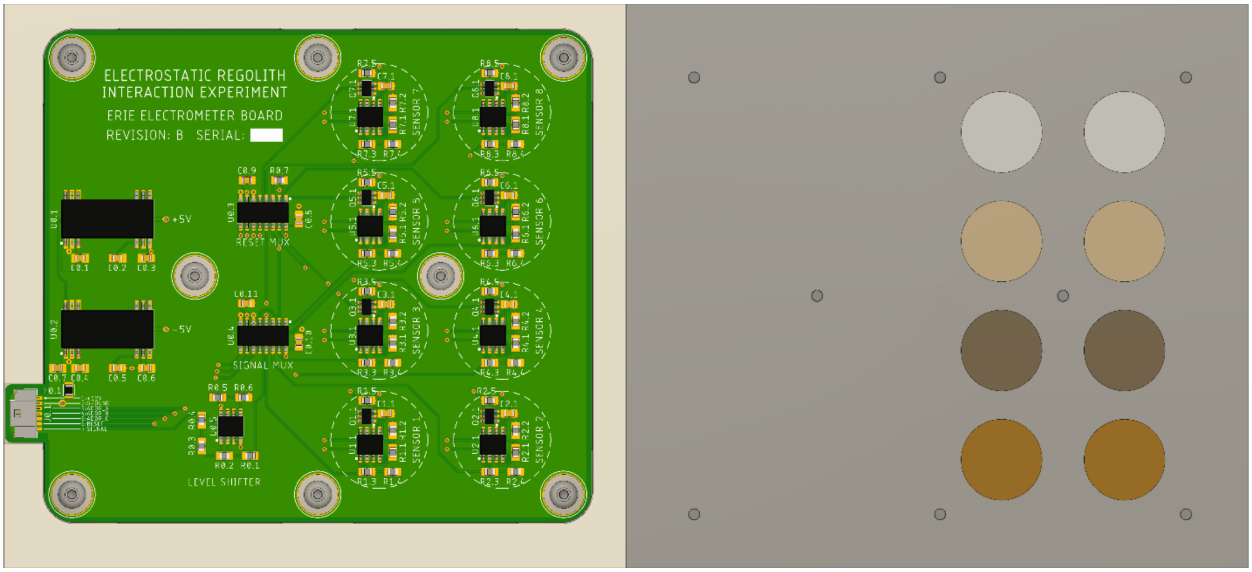

Figure 6. Electrostatic Regolith Interaction Experiment (ERIE) door with triboelectric sensors integrated in an array

Conclusions

Vehicles moving on the lunar regolith during lunar exploration activities will develop electrostatic charges due to the interaction with the lunar soil and with the lunar plasma environment. This plasma environment will also determine how the charge developed on the rover wheels will dissipate. Laboratory vacuum tests with the MSI indicate that the charge that will be developed on a large class of polymer materials placed on the lunar surface can be predicted. Moreover, the MSI will provide direct measurements of the ion flux and electric field strength in the vicinity of the triboelectric sensors, providing information on the electrostatic environment that will affect the dissipation of charge from these polymers. This information should be of help to mission planners.

References

---

[1] Manka, R.H., "Plasma and Potential at the Lunar Surface,", *Photon and Particle Interactions with Surfaces in Space*, Grard Springer, NY, 1973, pp. 347–361.

[2] Halekas, J.S., Bale, S.D., Mitchell, D.L., and Lin, R.P., "Electrons and Magnetic Fields in the Lunar Plasma Wake," *J. Geophys. Res.*, Vol. 110, 2005, A07222.

[3] Farrell, W.M., Stubbs, T.J., Vondrak, R.R., Delory, G.T., and Halekas, J.S., "Complex Electric Fields Near the Lunar Terminator: The Near-Surface Wake and Accelerated Dust," *Geophys Res. Lett.*, Vol. 34, 2007, L14201.

[4] Stubbs, T.J., Halekas, J.S., Farrell, W.M., and Vondrak, R.D, "Lunar Surface Charging: A Global Perspective using Lunar Prospector Data," *Workshop on Dust in Planetary Systems Lunar and Planetary Institute*, 2005, p. 4070.

[5] Calle, C.I., *Electrostatic Phenomena on Planetary Surfaces*, IOP Concise Physics series, Morgan and Claypool Publishers, San Rafael, CA, 2017.

[6] Singer S.F. and Walker, E.H., "Photoelectric Screening of Bodies in Interplanetary Space," *Icarus*, Vol. 1, 1962, pp. 7–12.

[7] Halekas, J.S., Poppe, A., Delory, G.T., Farrell, W.M., and Horanyi, M., "Solar Wind Electron Interaction With the Dayside Lunar Surface and Crustal Magnetic Fields: Evidence for Precursor Effects," *Earth, Planets and Space*, Vol. 64, 2012, pp. 73–82.

[8] Halekas, J.S., Mitchell, R.P., Lin, L.L., Hood, M., Acuña, H., and Binder, A., "Evidence for Negative Charging of the Lunar Surface in Shadow," *Geophys Res. Lett.*, Vol. 29, 2002, p. 1436.

[9] Halekas, J.S., Delory, G.T., Stubbs, J.K., and Farrell, W.M., "Lunar surface charging during solar energetic particle events," *J. Geophys. Res.*, Vol. 114, 2009, A05110.

[10] Delory, G.T., "Electrical phenomena on the moon and Mars," *ESA Annual Meeting on Electrostatics*, Charlotte, NC, 2010, paper A1.

[11] Freeman J.W. and Ibrahim M, "Lunar Electric Fields Surface Potential and Associated Plasma Sheaths," *The Moon*, Vol. 14, 1975, 103–114.

[12] Farrell W.M. *et al*., "Concerning the Dissipation of Electrically Charged Objects in the Shadowed Lunar Polar Regions," *Geophys Res. Lett.*, Vol. 35, 2008, L19104.

[13] Winslow, R.M. *et al*, "Lunar Surface Charging and Possible Dielectric Breakdown in the Regolith During Two Strong SEP Events," *46th Lunar and Planetary Science Conference*, 2015, p. 1261.

---

[14] Jordan, A.P., Stubbs, T.J., Wilson, J.K., Schwadron, N.A., and Spence, H.E., “Dielectric breakdown weathering of the Moon’s polar regolith,” *J. Geophys. Res.* Vol. 120, 2015, pp. 210–225.

[15] Jackson, T.L., Farrell, W.M., and M.I. Zimmerman, “Rover Wheel Charging on the Lunar Surface,” *Advances in Space Research*, Vol. 55, 2015, pp. 1710–1720.

[16] Rhodes, D.J., Farrell, W.M., and McLain, J.L., “Tribocharging and electrical grounding of a drill in shadowed regions of the Moon,” *Advances in Space Research*, Vol. 66, 2020, pp. 753–759.

[17] Farrell, W.M. *et al*., “Anticipated Electrical Environment Within Permanently Shadowed Lunar Craters,” *J. Geophys. Res.*, Vol. 115, 2010, E03004.

[18] Buehler, M.G., Cheng, L-J., Orient, O., Gompf, R.H., Calle, C.I., Bayliss, J., and Rauwerdink, J., “From Order to Flight in Eighteen Months: The MECA/Electrometer Case Study,” *IEEE Aerospace Conference*, Big Sky, Montana, 2000.

[19] Cross, J., *Electrostatics*, IOP Publishing, Bristol, UK, 1987.

[20] Johansen, M.R., Mackey, P.J., Holbert, E., Clements, J.S., and Calle, C.I., “Characterizing the Performance of the Wheel Electrostatic Spectrometer,” *Proc. ESA Annual Meeting on Electrostatics*, Cocoa Beach, FL, 2013.

[21] Calle, C.I., “Sensors to characterize the properties of the Martian regolith,” Concepts and Approaches for Mars Exploration, Houston, TX, 2012.

[22] Johansen, M.R., Phillips, J.R. III, Kelley, J.D., Mackey P.J., Holbert, E., Clements, J.S., and Calle, C.I., “A Feasibility Study of the Wheel Electrostatic Spectrometer,” *Proc. ESA Annual Meeting on Electrostatics*, Cocoa Beach, FL, 2014.

[23] Colwell, J.E., “Low velocity impacts into dust: results from the COLLIDE-2 microgravity experiment,” *Icarus*, Vol. 164, 2003, pp. 188–196.