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Topical: The need for high accuracy dust charge measurements

Primary Author:
Lorin Swint Matthews, *Baylor University*
Telephone: (254) 710-2279 (office); (254) 315-0025 (cell)
Email: lorin_matthews@baylor.edu

Co-authors:
Justin Burton, *Emory University*
JR Dennison, *Utah State University*
Ranganathan Gopalakrishnan, *University of Memphis*
John Goree, *University of Iowa*
Christine Hartzell, *University of Maryland*
Truell W. Hyde, *Baylor University*
Tom Keaton, *Utah State University*
Uwe Konopka, *Auburn University*
Babak Shotorban, *The University of Alabama at Huntsville*
Xu Wang, *University of Colorado*

1. Background: Charged dust in space environments and its effect on lunar missions

Airless bodies such as the moon are usually covered by a layer of fine dust particles. Due to direct exposure to the solar wind and solar radiation, these dust particles are charged and may be lofted due to electrostatic forces (triboelectric charging may also occur due to human/autonomous activities). Electrostatic dust transport is suggested to explain a number of unresolved lunar observations, such as the lunar horizon glow [Criswell, 1973], the high-altitude streamers [Zook and McCoy, 1991], the low-speed dust detections during terminator crossings [Berg et al., 1976], and a recent observation of dust deposits on lunar rocks [Yan et al., 2019]. Electrostatic dust transport is also suggested to contribute to the origin of swirl-shaped high albedo markings on the lunar surface [Garrick-Bethell et al., 2011]. Beyond the Moon, electrostatic dust transport is thought to be responsible for the formation of 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], indicating this process as a universal phenomenon in the solar system.

Since the onset of lunar visits in the Apollo era, lunar dust has been recognized as a critical issue in exploring and developing the Moon. Harrison Schmitt, geologist and Apollo 17 astronaut, asserted, "Dust is the No. 1 environmental problem on the moon," [Wired, 2005]. Dust adhesion to technical surfaces (and even to biological surfaces like lungs) is greatly amplified by charge build up on insulating particles and surfaces, which greatly enhance electrostatic attraction. To alleviate the risks that dust imposes on space technology and personnel, we must understand dust’s physical properties. *High accuracy dust charge measurements are required to investigate the space-environment-induced charging and charge dissipation of highly insulating granular particulates* that are a primary component in most cosmic dust found in the universe, including Lunar and Martian regolith. Such charging directly impacts all areas of Lunar exploration and research, including but not limited to accelerated equipment degradation and failure and increased hazard to human health as the fine particles are introduced into lunar habitats.

2. Review of dust charging and transport

Primary Charging Currents – The charge acquired by an object is a function of the electrons and ions which impinge upon its surface. The flow of electrons and ions from the plasma to the surface are the *primary* charging currents. In a thermalized plasma consisting of electrons and ions at the same temperature, the lighter electrons have larger velocities than the ions and collide with the surface more frequently. Thus, surfaces exposed to plasma tend to charge to a net negative electric potential (when the electron temperature is low enough that secondary electron emission is insignificant). As the surface charges, the negative electrons are repelled and the ions are attracted to the surface, until eventually the flux of electrons and ions are equal on the average sense and the surface reaches its equilibrium potential. The night side of the lunar surface is typically charged to a negative potential as it is exposed to the plasma in the solar wind [Stubbs, et al., 2014]. A tenuous plasma sheath forms above the lunar surface that gives rise to an electric field structure close to the lunar surface. Particles lofted from the ground can potentially be levitated by this electric field and propagate far distances.

Photoemission – Another charging process which is relevant to the lunar surface is the photoemission of electrons. The dust on the dayside lunar surface is directly exposed to the high-energy UV photons and soft x-rays emitted by the sun. Photons with an energy greater than the work function of the grain material can excite and liberate electrons and thus constitute a *secondary* positive charging current [Kimura and Mann 1998]. The electrons are emitted isotropically from their point of origin with a range of energies [Hinteregger et al 1959; Grard 1973; Wrenn and Heikkila, 1973]. Photoemission causes the dayside surface of the moon to be charged to a positive potential, and the emitted electrons form a dense photoelectron sheath [Stubbs et al., 2014]. Figure 1 illustrates the charging processes relevant to the lunar surface.

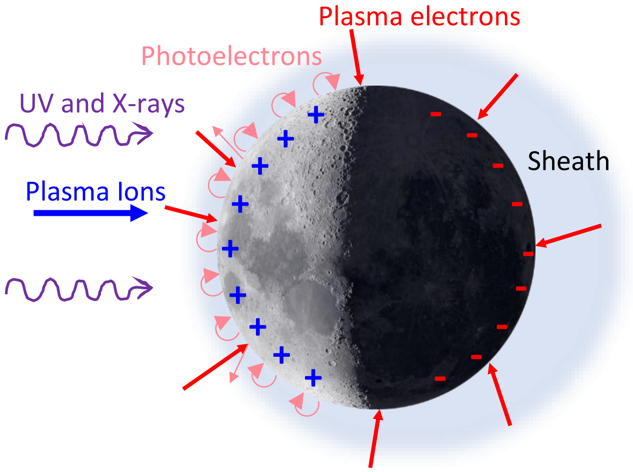

Figure 1. Charging processes acting on the moon's surface. Collection of electrons (red) and ions (blue) from the solar wind plasma results in the nightside charging to a negative potential with a tenuous plasma sheath. Solar UV and soft x-rays cause photoemission of electrons (light red) leading to a positive potential with a dense photoelectron sheath, causing most electrons to return to the surface.

Stochastic Charge Variations – The fine lunar dust particles of size 1-10 μm are strongly influenced by intrinsic stochastic fluctuations in charge, as electrons and ions are collected or emitted at irregular time intervals. Smaller grains ($a < 1$ μm) or grains in a tenuous plasma environment have relatively large charge fluctuations compared to the mean charg and can be sensitive to single additions of electrons or ions (Shotorban 2011, 2012; Matthews, Shotorban, and Hyde 2013, 2018).

Charging of irregular dust grains and grains in a surface layer – When dust grains are considered to be spherical, isolated objects, analytical expressions for the charging currents and equilibrium charge are easily obtained. Work on aerosol charging in atmospheric conditions reveal shape matters significantly for highly elongated particles [Li, 2021 and references therein]. Data and samples collected from space have shown that cosmic dust can have a porous fluffy structure, consisting of many small subunits [Greenberg & Hage, 1990]. In addition, lunar dust is very sharp and glassy [Heiken, 1991; Colwell, 2007]. Experimental and numerical research has shown that dust aggregates tend to acquire more charge when compared to spherical grains of the same mass [Ilgner 2012; Ma et al., 2013; Matthews et al., 2012]. Dielectric dust particles with irregular grain geometry, and multilayer conducting/dielectric structure also lead to evolving, complex, highly asymmetric (multipolar) charge distributions within grains and between particles.

The charge on an irregular dust aggregate or dust grains on a surface can be modeled by examining the currents to individual points on the surface of the grains (Fig. 2). Incident electrons and ions can impinge upon the surface from open "lines-of-sight" to each point. Phot-emitted electrons are ejected isotropically from an illuminated point on the surface. The majority of these electrons will escape the surface, but others may be collected by neighboring dust grains, resulting in very large local electric potentials [Wang, et al., 2016]. Small spatial and temporal charge enhancements (due to charge fluctuations) can lead to local electric fields which greatly influence the transport of dust (Fig 2c).

Dust transport – The transport of dust in the local lunar electromagnetic fields is ultimately affected by the charge-to-mass ratio of lofted dust particles, which can vary with the size distribution and charge state of the dust. Grains which are lofted in the photoelectron sheath above the lunar surface will have a time-dependent charge as they travel through the sheath. The irregular arrangement of charge on dust aggregates also affects the clumping and accumulation of dust on surfaces [Matthews Coleman Hyde, 2016; Xiang et al., 2021]. The transport of dust entrained in gas, such as dust stirred up by rocket exhaust or dust within a lunar habitat, will also be affected by the electrostatics forces acting on the charged dust.

The charge needed for dust particles to be lofted on the lunar surface was an open question for more than five decades. Application of a Patched Charge Model (PCM) greatly advanced our understanding of dust charging and lofting [Wang et al., 2016]. The PCM shows that photoelectrons emitted and re-absorbed within microcavities results in a buildup of large negative charges on the otherwise positive surface (Fig 2b). Subsequently, the repulsive forces between these particles are strong enough to cause their lofting. The PCM was verified experimentally [Wang et al., 2016; Schwan et al., 2017] and computationally [Zimmerman et al., 2016]. An extended-PCM was recently developed to explain the laboratory observations of dust mobilization in the presence of a magnetic field [Yeo et al., 2021].

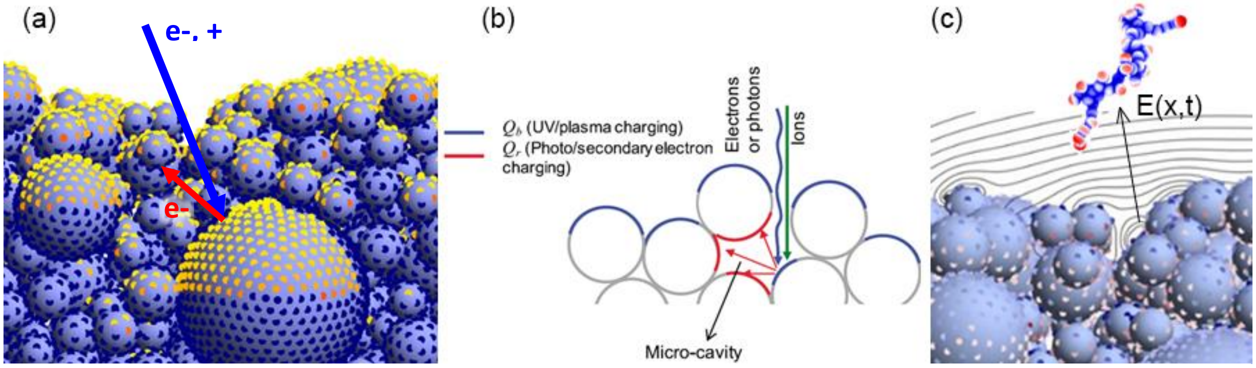

Figure 2. Charging and transport of lunar dust. The charge distribution over the surface can be considered by examining charging currents to discrete points on the grains. (a) Dust particles are charging by collecting electrons and ions from the plasma environment (blue arrow) and by emission of photoelectrons (red arrow) from illuminated surfaces (shown in yellow). (b) Illuminated surfaces tend to have positive charges (indicated in blue), while shadowed surfaces collect emitted electrons and tend to charge negatively (indicated in red). (c) The local variations in potential (shown by contour lines) can lead to strong electric fields allowing grains to be lofted from the surface. The arrangement of charge on an irregular dust grain affects the transport of dust in the electric field of the lunar sheath.

3. Open questions in charging and dust transport

Ion / electron distributions and lunar surface potential – Lunar dust is subject to charged particle fluxes from the solar wind, solar UV, x-rays and γ-ray, and galactic cosmic radiation. The incidence lunar fluxes differ substantially from other terrestrial, or near-earth environments due to the absence of atmospheric screening and magnetic fields. These fluxes can also be highly variable due to variations in solar activity. As the charging fluxes vary, the lunar surface potential and the associated plasma sheath will also change in time, affecting both particle charge and transport. It is also likely that the lunar surface will be exposed to high ion concentrations beyond 10^8 cm^{-3} (Khabarova and Zastenker, 2011). This implies that ions could be strongly coupled and the neglect of ion-ion interactions (as done for classically screened Coulomb potentials) on the charging process is not justified. *Measurements of the plasma environment on the lunar surface are crucial to understanding the charging and transport of lunar dust.*

Charging of small grains (charge of 10-100 e) – Currently only the charging and lofting of dust particles larger than 1 micron with a charge on the order of 1000 electrons and larger have been measured. The charge of submicron- and nanometer-sized dust particles is expected to be small, in a range between 10-100 e^-, and have never been directly measured. Determining the charge on small grains presents particular challenges. As noted above, stochastic charge fluctuations are significant and can lead to momentary positive charges that promote coagulation or growth of dust to larger sizes. Grains with low charge levels are especially susceptible to the effect of image or polarization forces acting on the colliding charged (ion/e) particles. These effects require sophisticated modeling and experimental methods to determine the charging behavior. Small dust particles are expected to have higher launch velocities and thus travel longer distances [Carroll et al., 2020; Hood et al., 2022], which may be responsible for high-altitude streamers on the lunar surface and the formation of high-albedo lunar swirls, for example. High-accuracy charge measurements of these small dust particles are needed to help us understand their dynamics in order to explain these observations.

Material Effects – There is a need to develop a broader understanding of the effects of materials on grain charging. Conducting materials allow free movement of surface charge, in contrast to non-conducting materials. This influences the forces experienced by the impinging electrons and ions. Particulate properties such as size, surface roughness, angularity, porosity, conductivity, layering, compactness and cleanliness also affect electron yield. Particulate size, as compared with energy-dependent electron penetration depth, is expected to affect the amount and spatial distribution of deposited charge, and thereby affect yields of charged particles [Wilson, 2013; Olano, 2019]. Preliminary studies should be conducted for homogenous, well-characterized particles. Initial studies on spherical particles made of insulating material should then be compared to more irregular particles with broad ranges of particle size distribution and aspect ratio, and finally to a variety of lunar dust samples with varying composition and size distributions.

Electron yield of lunar dust – Limited measurements have been made on samples of bulk lunar dust for electron yield [Anderegg, 1972; Willis, 1973; Dukes, 2013; Gold, 1979], photoyields, [Willis, 1973; Poppe, 2010; Sternovsky, 2008; Feuerbacher, 1972; Abbas, 2006] and plasma interaction [Sternovsky, 2008]. These studies already indicate that sample charging significantly limit the validity of preliminary results and that additional measurements on other more diverse types of lunar materials were necessary [Dukes, 2013; Anderegg, 1972; Feuerbacher, 1972]. Measurements of electron emission from electrical insulators, such as most lunar material, is made more difficult due to the existence of time-dependent charges with unknown lifetimes and mobility [Dukes, 2013]. Furthermore, it is difficult to elucidate the effects of small grain size and shape or the direct consequences that dust geometry had on these factors [Richterová, 2008; Abbas, 2010]. Accurate and precise measurements and modeling of electrical properties of lunar dust and simulants are required. To characterize exposure to the space environment of ionizing particles, measurements need to be performed for total electron yield, secondary electron yield, backscattered electron yield. Electron emission spectra and electron yield decay curves need to be determined over the expected energy range that are typical for space environments, 10 eV to 30 keV. Photoyields need to be measured for incident higher flux electromagnetic radiation, especially for UV photons of ~4-7 eV and H Lyman alpha (10 eV) radiation.

4. Experimental challenges

How do you measure the charge without changing the charge? Dust particles immersed in a plasma are coupled to external fields through their charge. However, the charge can vary substantially in different parts of the plasma, for example, within the plasma sheath near a surface. Additionally, the charge is a dynamic quantity; it is often calculated by balancing kinetic rates of ion and electron collisions, and in low pressures the relaxation time can be comparable to the motion of the particle itself. How does one measure this charge? Electrostatic probes can be used to measure surface voltage [Hodges, 2014] or displace and excite motion of a particle, yet the probe also alters the plasma environment and thus alters the charge. Developing non-perturbative ways to measure or estimate the charge through the particle dynamics alone will allow for use in a wide variety of systems, especially in microgravity environments where simplicity and efficiency in experiments are key.

How do you measure the charge without moving the particle? Particles can be mechanically or electrostatically perturbed or scattered off one another in order to estimate interaction potentials and thus the particle charge. These methods have been successfully used in the past [Walch, 1994; Konopka, 1997; Yousefi, 2014] but require user manipulation of some sort. Alternatively, due the stochastic fluctuations of the environment, the Brownian-like motion of dust particles can also be analyzed to estimate charge. This is done most easily in two and multiparticle systems, with the assumption that particles are identical [Mukhopadhyay, 2012]. The newest frontiers involve hydrodynamic modeling of ions and electrons (thus electric fields) in plasma sheaths combined with dynamical inference and machine learning techniques [Douglass, 2012; Alves, 2020; Yu 2021]. These methods aim to infer interaction laws and charge from the motion of single particles through imaging alone, and have the advantage of being scalable, combining information from many particles in a single field of view for more reliable measurements.

How do you measure the charge of grains on a surface? Previous charging models treated a dust particle resting on a surface as part of the surface. The charge on a dust particle was set to be a fraction of the charge of the total surface area [Flanagan and Goree, 2006], which is determined by the sheath electric field above the surface. However, as pointed out above, the charge on the surface can have substantial temporal and spatial variations, affecting secondary electron emission [Olano, 2019; Keaton 2021] and dust lofting. Thus measuring the local variations on the microscale becomes important in understanding subsequent dynamics of lofted grains.

5. Summary of research opportunity

Dust mitigation strategies, tests and simulations rely critically on accurate measurements of the plasma environment, electron yield, and dust charge. Terrestrial analogs of lunar conditions yield excellent starting points to understand the lunar environment. Without realistic measurements of the conditions on the lunar surface, modeling and measurements of practical applications and mitigation strategies are largely inaccurate and ineffective. Results of the proposed studies will also advance modeling of more fundamental processes, such as understanding electrodynamic processes in the interstellar medium, the role of dust in the origin and evolution of the solar system, comets, planetary rings, and plasma surface interactions.

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