BEHAVIOR OF CHARGED DUST IN PLASMA AND PHOTOELECTRON SHEATHS

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ABSTRACT

Dust particles in the regoliths of planetary satellites, asteroids, and ring particles can become charged due to photoemission from solar ultraviolet photons, solar wind currents, and, in some cases, magnetospheric electrons. A surface potential is created on the surface of airless bodies in the solar system, such as the Moon, due to these same currents. This leads to a plasma sheath over the nighttime surface and a photoelectron layer over the daytime surface. Charged dust particles injected into this near-surface plasma environment are affected by the electrostatic force as well as gravity. This can lead to transport of dust and levitation of particles above the surface. Lunar electrostatic dust dynamics have been proposed for several observed dust phenomena [1-6]. Similar phenomena may play a role in the spokes of Saturn's rings [7, 8] and in the formation of smooth deposits in the floors of some craters on the asteroid Eros as observed by the NEAR-Shoemaker spacecraft [9].

1. OBSERVATIONS

Observations from the lunar surface by several of the Surveyor landers revealed a horizon glow over the western horizon shortly after sunset [3, 4, Figure 1]. An analysis of the geometry of these images and the calculated levitation heights and trajectories for charged dust suggest that these observed dust particles may be up to tens to hundreds of meters above the lunar surface.

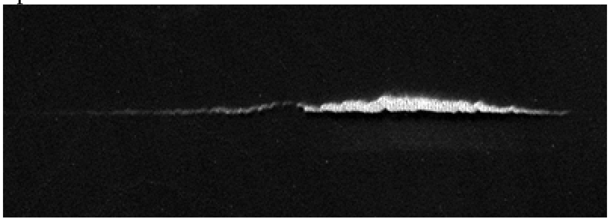

Figure 1. Observation of the Western horizon by the Surveyor 7 spacecraft shortly after sunset showing horizon glow. The glow is sunlight scattered by dust particles launched off the lunar surface by electrostatic forces.

The Lunar Ejecta and Meteorites Experiment (LEAM) detected increased signals near sunset and sunrise that have been interpreted as lunar dust particles moving over the surface [1, 2]. While they may be levitating or partially suspended, levitation may not be required to explain the observations of lunar horizon glow and the impacts detected by LEAM. Rather, the particles may simply be on modified ballistic trajectories following electrostatic launching off the surface.

The NEAR-Shoemaker spacecraft observed smooth flat deposits, called ponds, in the floors of medium-sized craters. Observations are consistent with these deposits consisting of dust particles though they do not rule out cm-sized particles. These ponds are in topographic lows that are therefore also regions of changing illumination and shadowing over the course of an Eros day. The location of ponds is also correlated with latitude and local gravitational acceleration [10]. Electrostatic transport may be particularly effective near the terminator where strong local electric fields can be generated. The latitudinal distribution of ponds on Eros may be related to the high obliquity of Eros (89 degrees) and the particular illumination and shadowing history of craters at those latitudes. In addition to the ponds, regolith (possibly dusty) aprons were observed adjacent to some large boulders and ejecta blocks on the surface of the asteroid. Topography and shadowing may play a role in the accumulation of regolith in these areas.

2. SIMULATIONS

We simulate the trajectories of charged dust particles lifted off a dusty regolith, including gravitational and electrostatic forces as well as time-dependent charging of the grains. We have expanded the two-dimensional model of Colwell et al. [9] to three dimensions. This allows us to simulate craters at arbitrary latitudes on an obliquely rotating object such as Eros throughout its orbital period. We integrate the equation of motion in the vertical direction, *z*,

$$\frac{d^2z}{dt^2} = \frac{Q_d}{m_d}E - g \qquad (1)$$

where Q_d is the time-dependent charge of the grain, m_d is the grain mass, E is the spatially varying electric field due to the surface charge and the ambient plasma, and g is the local acceleration due to gravity. We give the dust particles an initial launch velocity from the surface that determines their constant horizontal velocity. At the moment we treat this as a free parameter, but in future

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simulations we will base this value on a calculation of the forces acting on the particle when it is still in contact with the surface. This will be based in part upon experiments currently underway to measure the charge of grains on the surface. The charge, Q_d, is calculated from the charging equation, $dQ_d/dt=I_{pe}-I_e-I_{sw}$, and the currents I_{pe}, I_e, and I_{sw} are due to photoemission from the particle, collection of electrons from the photoelectron sheath, and collection of solar wind electrons, respectively [9]. We assume that the electric field vanishes over shadowed regions, so that particles there are on purely ballistic gravitational trajectories.

While this abrupt transition in the plasma properties over dayside shadow boundaries is an idealization, it captures the relevant physics. In shadowed regions there is no photoemission from the surface so the surface does not acquire the positive charge that sunlit surfaces do. It is possible, depending on the geometry and length scales, that shadowed regions may collect enough solar wind electrons (or photoelectrons from neighboring illuminated surface units) to acquire a significant negative charge. In this case the electric field is directed toward the surface rather than away from it, and particles that are positively charged due to their own photoemission would be attracted to the surface. Particles over shadowed regions may well be illuminated owing to their altitude above the local topography, so they would remain positively charged. The net effect is still such that shadowed regions are a sink for charged dust.

Dust particle trajectories and charges are integrated until the particle leaves the simulation space or hits the surface. The location of the particle's impact on the surface is recorded, and by simulating a large number of particles with different initial conditions (location, time, and velocity of launch) we compute a distribution of dust on the surface. Because Eq. (1) can equal zero, dust particles may be levitated above the surface and fall to the surface only in shadowed regions where the electric field vanishes. In this way electrostatic mobilization of dust may lead to transport of dust into shadowed areas. More generally, strong electric fields at the surface can lead to mobilization of dust which allows the particles to settle in topographic lows such as craters.

Our numerical simulations confirm a tendency for dust to accumulate in shadowed regions, suggesting that this charged dust transport may play a role in the dust deposits seen in craters and adjacent to large boulders on Eros. Figure 2 shows the distribution of particle landing locations for a simulation of a crater on the equator of an asteroid with an obliquity of 60 degrees. Particles were launched only at the start of the day. Landing locations are concentrated in the area of the crater that is shadowed in the morning.

Particles in some conditions may be stably levitated over the surface with the electric force balancing gravity (Eq. 1). The altitude for stable levitation depends on the inverse square of the particle size assuming a Maxwellian distribution of photoelectron velocities [9]. We find that the typical stable levitation heights are much higher than previously assumed for most particles small enough to be levitated (Figure 3). Dust responsible for the lunar horizon glow (Figure 1) may therefore be tens or hundreds of meters above the surface, rather than hovering at the Debye scale height of ~ 1 m above the surface. The glow may also be due to particles on nearly ballistic trajectories that were merely lifted off the surface by electrostatic forces [3, 11].

On Eros we find levitation possible for particles smaller than 1 μm at heights of tens to hundreds of meters. Whether particles levitate or not, there is a net transport of dust into shadowed regions where there is no surface photoemission and therefore no vertical electric field to counter gravity. The timescale for dust transport on Eros through this mechanism is short enough to explain the Eros crater dust deposits, though the simulations do not reproduce the smooth distribution of dust in detail. Other processes such as impact-induced seismic shaking may also play an important role.

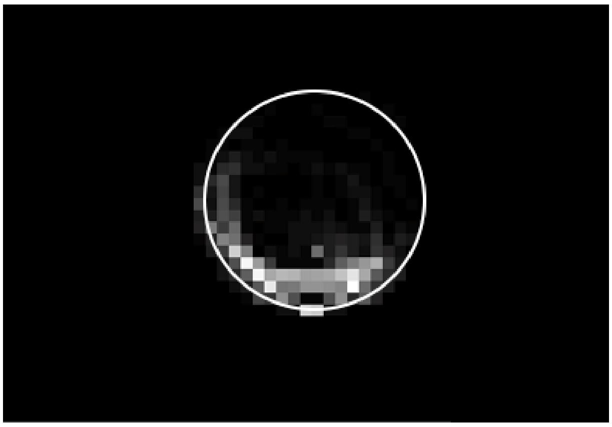

Figure 2. Distribution of landing positions for dust particles launched shortly after sunrise in a simulation with a crater on the equator of an object with an obliquity of 60 degrees. Dust is concentrated in the shadowed area near the crater rim. The Sun is below the crater in this view and moves from left to right.

From the geometry of shadowing and solar illumination over the course of an Eros year, the obliquity of Eros produces preferential transport of dust into craters through electrostatic transport for craters near the equator. This is consistent with the observed distribution of ponds on Eros [11]. However, the irregular global shape of the asteroid may also play a role in the distribution of dust and regolith on the surface. Our current simulations are local, and global simulations are needed to study dust migration on Eros under electrostatic and gravitational forces.

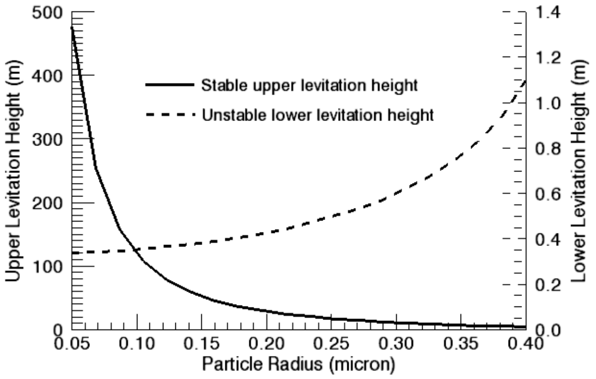

Figure 3. Calculated levitation heights for charged dust in the lunar photoelectron layer. The stable levitation height (solid line) is tens of meters for all particles except those close in size to the largest particle that can be suspended by the electric field.

3. EXPERIMENTS

We have performed experiments on levitation and transport of charged dust in a plasma sheath as well as charging of dust in a photoelectron sheath. The surface in a laboratory plasma device has a negative potential relative to the plasma due to the smaller mass and therefore higher velocity of the electrons than the ions in the plasma. The sheath region is the transition from the surface potential to the plasma potential. The potential profile within the sheath is found by using Poisson's equation with appropriate models for the electron and ion densities. Discussions of the charging equations and conditions for levitation have appeared in the literature for objects in space [8, 12, 13] and for laboratory plasmas [14-16]. The height at which particles are levitated are found from these models, and the models agree with experiments. These models, however, are one-dimensional and cannot account for horizontal motion.

We experimentally explore horizontal transport of charged dust in a plasma sheath using a stainless steel vacuum chamber 51 cm in diameter and 28 cm in height (Fig. 4) that has been described previously [15, 16]. The chamber is evacuated to a base pressure of 1.5×10^{-6} Torr by a turbomolecular pump and the working pressure is 1.5×10^{-4} Torr of argon. The plasma is generated by primary electrons from heated filaments biased to –40 V and emitting 350 mA.

We placed 1-cm diameter circular patches of JSC-Mars-1 dust, a Martian regolith simulant, on a graphite plate in the vacuum chamber and exposed it to plasma. The results presented in Figures 6 and 7 are for JSC-Mars-1, but similar results were observed for JSC-1, a lunar regolith simulant. We determine the amount of dust by scanning digital images of the dust pile. This allows us to detect the density of dust on the surface up to a saturation point where the addition of dust does not increase the observed brightness. We use JSC-Mars-1 because of its greater visibility on the black graphite plate.

The dust piles spread horizontally in the first 10 minutes of exposure to plasma. This spreading is due to the dust particles charging to a potential that is significantly different from that of the conducting surface. This generates an electric field with a horizontal component that transports the dust away from the initial pile. We also performed experiments with copper dust on the graphite plate. This conducting dust on a conducting surface remains at the same potential as the surface so there is no electric field at the dust-surface boundary, and no transport is observed.

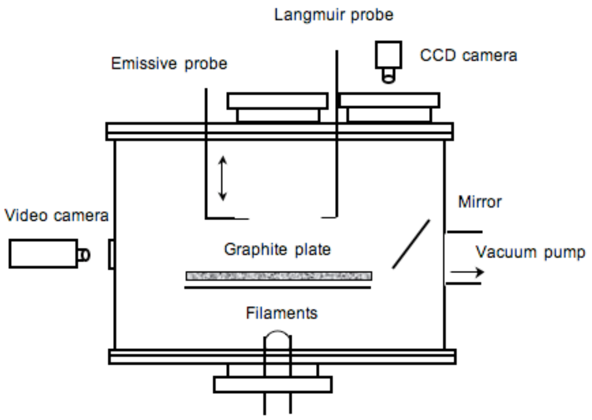

Figure 4. Schematic diagram of the plasma sheath experimental apparatus.

We measured the potential above a glass disk used as a proxy for the insulating dust (movement of the dust resulted in particles hitting the emissive probe used for potential scans when scans were made over the dust patches). These scans show that the insulating disk charges to a constant potential that is nearly independent of the graphite plate potential (Fig. 5). The result is a potential gradient at the boundary of the disk. Because the graphite plate is more negative than the insulating disk (or dust), the horizontal component of the electric field is radially outward so grains that move outward are positively charged. The spreading of the dust pile proceeds until the potential transition from the graphite plate to the insulating disk is gradual enough that the resulting electric field is too weak to result in transport of dust (Fig. 6).

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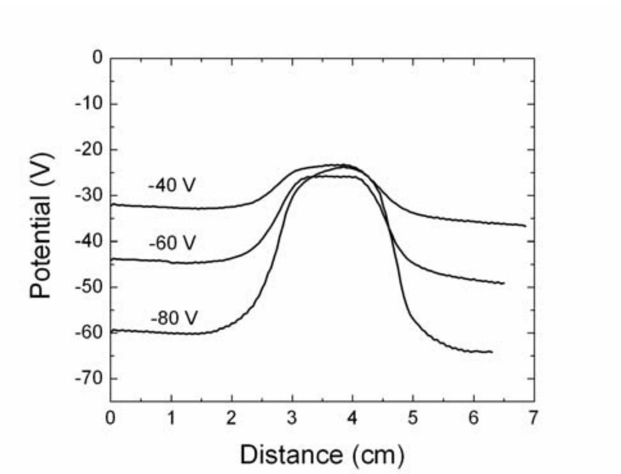

Figure 5. Horizontal scans above a glass plate for graphite plate bias potentials of -40, -60, and -80 volts. The slight fall in the potential with increasing distance is a consequence of the probe sagging and becoming closer to the plate as a greater length of probe is inserted into the device.

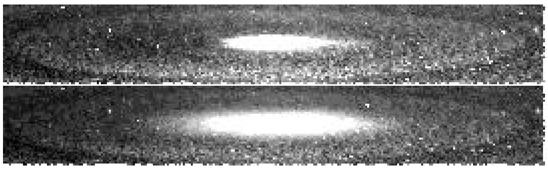

Figure 6. Dust on a graphite plate before (top) and after (bottom) exposure to a plasma sheath environment for 80 minutes.

Experiments where the dust is placed on a sloped surface produce the expected transport of dust down the gradient in gravitational potential energy.

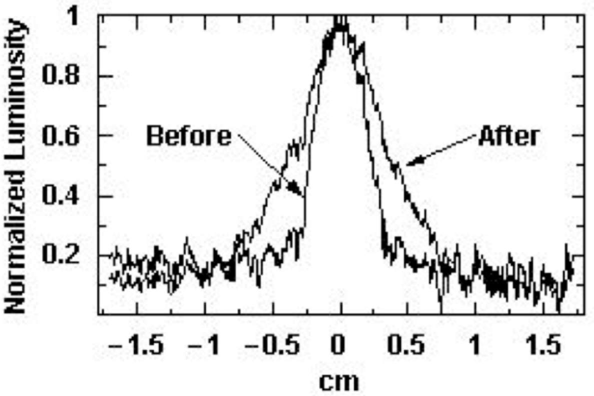

Figure 7. Scans of images (Fig. 6) of dust before and after exposure to a plasma sheath environment. The spreading of the dust leads to lower electric field strengths at the dust-surface boundary.

4. DISCUSSION

Observational evidence from several surfaces in the solar system points to charged dust particles lifting off the surface. Electrostatic effects can facilitate the transport of dust down gravity gradients and into regions of different electrical properties, such as different surface materials or shadowed regions. Terminator crossings are associated with increased dust activity on the lunar surface, but micron-sized dust observed above the lunar horizon travels to much higher altitudes than previously estimated [see also 10].

Our experimental results suggest that horizontal transport of dust in a plasma sheath can occur where there are abrupt transitions in the surface potential. While we have introduced such transitions in our experiments through the use of different materials, equivalent potential transitions may occur on the Moon or other bodies not through compositional inhomogeneities but through changes in the plasma conditions above the surface. In particular, at the terminator some tilted surface elements may be exposed to sunlight at high incidence angles while neighboring elements are in shadow. The illuminated elements will emit photoelectrons and charge positively relative to the shadowed areas. The net result is the same situation studied in our laboratory experiments: a boundary between surface units with different surface charges. These terminator regions may therefore have strong, temporary, localized electric fields that can lead to mobilization and transport of dust like that we observed in our experiment. The net effect is for the dust to move in such a way to make a more shallow gradient in surface charge. Net transport depends on the charge of dust on the surface and the detailed topography.

Our numerical simulations show that shadowed regions such as craters can act as traps for charged dust. The ponds on Eros, for example, lie at the topographic lows at the centers of craters, which is not the region that is most shadowed. Electrostatic mobilization and transport of dust may help small particles move to topographic lows and get them into the craters, but additional processes such as seismic shaking and downslope movement are likely needed to explain the dust ponds on Eros in detail. Further numerical simulations as well as experiments with more variegated simulated topography are planned to investigate the role of this process in producing observed dust distributions on asteroids. The conditions under which lunar regolith is lifted off the surface and its subsequent dynamics is also being studied with these experimental and numerical techniques. Future missions to the lunar surface will have to contend with the charged dust environment near the lunar surface. Understanding the charging processes and transport mechanisms for dust in a plasma sheath will enable mitigation strategies for working in dusty planetary environments.

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