Surface Dynamics on Small Bodies: Electrostatic versus Gravitational Fields

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Abstract

There has been evidence of dust levitation in space, first on the Moon. At asteroid Eros, dust craters, or ponds, have been observed by the Near Earth Asteroid Rendezvous mission (NEAR) in 2001, suggesting the presence of electrostatic forces able to alter the regolith distribution. Since then, work has been done to simulate and partially reproduce the phenomena observed. More recently, observations from the Hayabusa spacecraft validate predictions on particle sizes due to solar interaction. In future missions to these bodies, we hope for additional close approaches, touchdowns and mobile landers. Thus local gravity and dust properties become a greater concern for the success of the mission. As an asteroid rotates, it induces charging cycles from photoemission of electrons and collection of solar wind electrons and ions. Hence, the local surface of the small body goes from positive to strongly negative potential. However, to date, there is still little known about the coupling between electrostatic force and the low gravitational attraction on small bodies. In this paper, we revisit the modeling and theory of dust levitation for Near Earth Asteroids, and we give a measure of relative importance of the electrostatic and the gravitational fields.

Motivation

Surface properties of small body are now of more concerned due to sample return missions, the Hayabusa Follow-on missions for instance, and the possible deployment of landers \textsuperscript{9}. From a technological point of view, dust collecting on solar cells can degrade their performance, reduction of light for optical systems may interfere the navigation procedures, and dust coating in moving mechanical parts can prevent them from moving. From a scientific point of view, dust and electrostatic may affect the interpretation of remote sensing data while electrostatic can give more insight into the dynamics of regolith on the surface.

Over the past decades, there have been spacecraft missions and studies reporting such dust phenomena. For instance, observations on the Moon from the Surveyor spacecraft provide evidence of dust levitation, most likely associated with electrostatic charge and electric field near the surface \textsuperscript{16}. In addition, features near small craters on Eros may indicate dust transport \textsuperscript{2}. Since the gravitational pull from small bodies are of the order of $10^{-4}$, the electrostatic field may play a critical role in the distribution of matters around these small solar system bodies. From the Hayabusa spacecraft at Itokawa, we can correlate slope vectors from local gravitational and centripetal accelerations with the downslope motion of particles \textsuperscript{15}. At such proximity, the local electric field must play an important role in the dynamics of these particles.

In the following sections, we give an overlook of the surface conditions in a near zero gravity environment, and the influence of electrostatic charge compared to gravitational acceleration.

Electrostatic Charge on Small Bodies

The first evidence of dust levitation and possible electrostatic charge on the Moon came from the Surveyor and the Apollo missions, which have recorded dust grains suspended above the lunar surface \textsuperscript{16, 3, 5, 4, 18}. Clementine has also given more recent images of the Moon dust \textsuperscript{12}. Subsequent to the Surveyor and Apollo observations, modeling and experiments have been done for lunar applications especially, starting in the 60s.

Studies of other small bodies have started to show similar dust phenomenon. For instance, spokes in Saturn’s rings suggest dust and particles levitation \textsuperscript{6, 11}. On the asteroid Eros, as observed by the NEAR mission, dust craters, or ponds, are believed to have formed from dust transport \textsuperscript{17, 14}. Observations from the Japanese Hayabusa spacecraft validate predictions on particles size observed due to interaction with solar effects \textsuperscript{15}.

Dr. Pascal Lee made a first model estimate of electrostatic processes on asteroids in the Main Belt population \textsuperscript{10}. Later on, Colwell et al. at UC Boulder simulated 2D and 3D dust levitation in a photoelectron sheath and transport to explain the formation of ponds on Eros \textsuperscript{2}. Colwell’s group also performed experiments of dust particles in Earth gravity environment, and others with plasma sheath measurements, photoelectric charging in vacuum, and applications for Moon environment studies. Other groups have now started lunar dust levitation. For instance, the Kyushu Institute of Technology recently reported on spacecraft charge and lunar dust levitation \textsuperscript{8}.
Comparing the Moon and Small Solar System Bodies

Even though dust phenomena on the Moon and on small bodies look similar, a few differences need to be outlined. To this date, most studies and experiments have looked at lunar and/or Mars applications, with a few for the Main Belt Asteroid population (for instance see [16, 3, 10]). When NEAR arrived at Eros, it was beyond the orbit of Mars, whereas current targets of interest are between 1 and 1.3 AU [9]. In addition, the features studied and simulated on Eros are about the size of Itokawa [17, 2].

For modeling the surface environment, the gravity field has been taken as constant, and in higher gravity environment than for current targets. For instance, Eros gravity is about 0.55 cm/s², while Itokawa is 0.001 cm/s². On small asteroids, this leads to larger amount of dust levitated and transported, and on larger height scale (100s meters). The small bodies of our solar system, such as asteroids, are usually under a fast cycle or time scale for dust transport, having a spin period between 5 and 30 hrs [13]. Hence, small bodies are in fact under a possibly rapid resurfacing process.

Electrostatic versus Gravitational Fields in Extremely Low Gravity Environment

Charging Cycles on Asteroids

Charging currents on the surface are photoemission of electrons and collection of solar wind electrons/ions. The net result is a positive surface charge on the dayside where photoemission dominates and a negative surface charge on the nightside where collection of solar wind electrons dominates. As an asteroid rotates, it induces charging cycles, going from positive to strongly negative potential.

Dust charging can be expressed as follows:

\[
\frac{dQ_d}{dt} = I_{pe} - I_e - I_{sw},
\]

(1)

where \(I_{pe}\) is the current from the photoelectrons emitted by the grains, \(I_e\) represents the current from photoelectrons to particles, and \(I_{sw}\) is from the collection of solar wind electrons.

The electric field strength is function of the height above the surface,

\[
E(z) = 2\sqrt{(2)}\phi_s\lambda_D \left(1 + \frac{z}{\sqrt{(2)}\lambda_D}\right)^{-1},
\]

(2)

where \(\lambda_D\) is the Debye length at the surface, \(\Phi_s\) is the surface potential, and \(z\) is the height above the surface.

Surface potential is estimated to vary from 5 V during the day to negative 10 to 40 kV at night. In Fig. 1, we compare the electric force compared to gravitational force for both Itokawa and Eros. In the case of Itokawa, particles of order 100 µm can be stably levitated. In the case of Eros, particles of 1 – 2 µm in size can be stably levitated [2].

![Figure 1: Electrostatic vs gravitational force for a) NEA being 100s of meters in size, like Itokawa, and b) Eros.](image)
Proximity and Surface Dynamics on Small Bodies

We included the effect of electrostatic charge in the equation of motion of a particle moving on a small sub-km asteroid. To simulate surface motion, we use a standard coefficient of restitution and friction model; as the particle bounces, it looses energy through impact and surface roughness.

The problem is similar to the asteroid orbiter problem, although the orbit is kept close to the surface, including a surface constraint. Using impact dynamics, it is possible to calculate the time and distance for a particle to settle. It is also useful for analytical prediction of motion and to terminate the numerical simulations (see [1] for a description of surface dynamics and control of hoppers/particles in low gravity). The time and distance to reach a stop are now a function of particle sizes through the electrostatic force described in previous sections.

Previous work by Guibout and Scheeres used classical dynamics and geometrical analysis to investigate the stability of surface equilibrium points for a rotating ellipsoid [7]. In their work, it is shown that equilibrium points can be along all three principal axes, and that stability is function of the ellipsoid gravity and spin rate. In later studies, Bellerose and Scheeres showed that for small perturbations, under certain conditions a moving object tends to stay closer to a stable equilibrium point and further away from an unstable one [1].

Accounting for the surface charge, we can derive new expressions for the stability of the surface equilibrium points. Due to the strong electric field at the terminator, particles may be swept out as shown on Fig. 2. As future work, we want to derive new stability conditions, and find a periodicity that makes any equatorial edges loose their stability properties when it is close to the terminator state.

![Figure 2: Micron-sized particle under the influence of electrostatic charge.](image)

Conclusions and Future Work

We modeled and implemented the surface electrostatic charge for very low gravity bodies. We find that near field and surface dynamics are easily modified by solar interactions creating surface charge. Compared to earlier theoretical results, and accounting only for the asteroid spin, shape, and its gravity field, the stability of surface dynamics is function of particle sizes and latitude of motion w.r.t the ecliptic plane.

As future work, we want to refine the modeling and transition between equatorial and terminator regions on small bodies, or where the surface goes from day to night. We also want to refine the influence of ejection velocity on the dynamics of particles.

Acknowledgements

Julie Bellerose acknowledges support from the Japan Society for the Promotion of Science Prostdoctoral Fellowship.
References


