EPJ Web of Conferences **140**, 14009 (2017) DOI: 10.1051/epjconf/201714014009
Powders & Grains 2017

Electrostatic forces on grains near asteroids and comets

Christine Hartzell[1,★] and *Dylan* Carter[1]

[1] *Department of Aerospace Engineering, University of Maryland, 3178 Martin Hall, College Park, MD USA 20904*

Abstract. Dust on and near the surface of small planetary bodies (e.g. asteroids, the Moon, Mars' moons) is subject to gravity, cohesion and electrostatic forces. Due to the very low gravity on small bodies, the behavior of small dust grains is driven by non-gravitational forces. Recent work by Scheeres et al. has shown that cohesion, specifically van der Waals force, is significant for grains on asteroids. In addition to van der Waals cohesion, dust grains also experience electrostatic forces, arising from their interaction with each other (through tribocharging) and the solar wind plasma (which produces both grain charging and an external electric field). Electrostatic forces influence both the interactions of grains on the surface of small bodies as well as the dynamics of grains in the plasma sheath above the surface. While tribocharging between identical dielectric grains remains poorly understood, we have recently expanded an existing charge transfer model to consider continuous size distributions of grains and are planning an experiment to test the charge predictions produced. Additionally, we will present predictions of the size of dust grains that are capable of detaching from the surface of small bodies.

1 Introduction

Small planetary bodies, such as asteroids and comets, have increasingly become attractive targets for space exploration missions because of their scientific value, potential hazard to Earth, and as a possible human exploration destination (as an intermediate step before Mars). The dust on the surface of small bodies (called regolith) is of particular interests as this is the material with which landing vehicles will interact. Due to the small mass and resulting weak gravitational acceleration of small bodies, it has recently been shown by Scheeres *et al.* that nongravitational forces, specifically cohesion, will drive the behavior of the regolith [1]. Essentially, grains as large as centimeters in size on 500-m scale asteroids will behave like flour does on Earth [1].

In addition to cohesion, grains on small bodies will be influenced by electrostatic forces. Asteroids typically do not have magnetic fields. Thus, the surface of an asteroid interacts directly with the solar wind plasma and the solar UV radiation. The solar wind plasma tends to charge surfaces negatively. However, the solar UV radiation causes the regolith to photoemit, producing a net positive charge on the day-lit surfaces of the asteroid. The positively charged surface attracts electrons, resulting in a region of increased electron density near the surface called the plasma sheath. The plasma sheath serves to shield the charged asteroid surface from the free-stream plasma that has an electric potential of zero. Plasma sheaths are frequently studied experimentally in a variety of plasma physics applications. The charge separation in the plasma sheath causes an electric field, which points away from the surface on the day-side [2, 3]. On the night side, there is a plasma wake due to the higher mass of the ions than the electrons, which also causes an electric field [4]. The plasma environment has been measured at the Moon by the ARTEMIS mission and at comet Churyumov-Gerasimenko by the ROSETTA mission, however, these measurements have been confined to regions outside of the near-surface plasma sheath. Given our undestanding of the plasma environment, regolith grains on the surface of a small body will be charged and exposed to an electric field. The product of the charge and the electric field is an electrostatic force. It has been hypothesized that if the electrostatic force is greater than cohesion and gravity, it may cause dust to detach from the surface [5, 6]. Recent work by Zimmerman *et al.* and Wang *et al.* have independently shown (computationally and experimentally, respectively) shown that grain-scale interactions with the plasma electrons may cause the development of significantly larger electric fields than predicted considering the interaction of the plasma with a flat plate [7, 8]. Additionally, if grains are released from the surface due to other causes (e.g. micrometeoroid bombardment or spacecraft activities), their trajectories will be influenced by the electrostatic force while the grain is within the plasma sheath (i.e. within about 10m-15m of the surface). Electrostatic dust lofting has been observed experimentally in the lab [6, 9], but there have been no conclusive observations of lofted dust *in situ* at small planetary bodies.

In addition to grain charging due to interactions of the surface of an airless body with the solar wind plasma, grains may also charge during spacecraft activities via tri-

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[★] e-mail: hartzell@umd.edu

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bocharging; the exchange of charge when grains collide or slide against one another. Planetary regolith grains are typically dielectric. While it is known that tribocharging between dielectric grains of the same material occurs, there is currently no prevailing theory of the physical underpinnings of this charge exchange [10]. Currently, the leading theory of same-material dielectric tribocharging is that the charge exchange is due to electrons transitioning from high energy states on one grain to low energy states on the second grain [11]. Given this physical mechanism of charge exchange, it is possible to create semi-analytical predictions of the level of charging in a mixture of grains. By improving our understanding of the dielectric same-material charging, we will be able to predict the level of grain charging induced by spacecraft activity and the subsequent interaction of grains with the local plasma environment.

2 Grain Lofting

Grains will detach from the surface of an airless body if the forces holding the grains to the surface are less than the forces acting away from the surface. For small bodies, the forces working to hold grains on the surface are gravity and cohesion, although the gravitational acceleration is not likely to be directly normal to the surface given the highly aspherical shape of most asteroids. Acting to detach the grain from the surface is the centripetal acceleration (which can be large for fast spinning bodies), electrostatic forces, and, under certain circumstances, gas drag. It has recently been found that some asteroids experience outgassing, in addition to the known outgassing of comets [12]. Figure 1 shows the relative magnitude of these forces as a function of grain size, considering a location at the far end of the large lobe on the comet 67P/Churyumov-Gerasimenko.

In Figure 1, the gravitational acceleration is calculated using a bi-ellipsoid shape model. The bi-ellipsoid approximation consists of a 2.5x2.5x2 km ‘head’ perched on a 4.1x3.2x1.3 ‘body’. The comet is assumed to rotate with a period of 12.4hrs about a rotation axis through the comet’s neck. The gas drag force on grains is modeled as:

$$F_d = 0.5\pi r_d^2 \rho C_d V_{rel}^2 \tag{1}$$

where a is the grain radius, ρ is the gas density, C_d is the drag coefficient (assumed to be 2, as in [13])), and V_{rel} is the relative velocity of the gas. For these calculations, the gas density is calculated assuming water molecules with a number density of 10^{17} m^{-3}. V_{rel} is assumed to be 300 m/s. The density and velocity numbers used are conservative when compared to the coma in order to allow us to explore other regions about the body. The drag force is assumed to act normal to the surface. The drag force may be neglected for most asteroids.

The electrostatic force is the product of the grain charge and the local electric field strength. We assume that the grain potential is 5 V and the local electric field is 5 N/C. These values are representative of the environment that we expect on a sunlit airless body, not considering any tribocharging [14]. Local shadowing or the presence of a bow shock will change the local plasma environment.

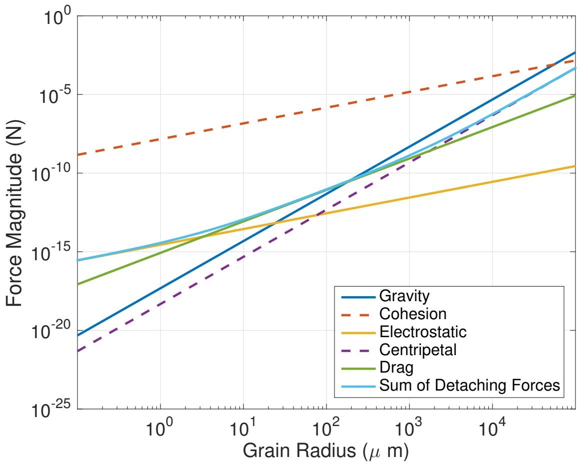

Figure 1. Relative magnitude of forces as a function of grain size on the surface of comet 67P/Churyumov-Gerasimenko. The gravitational acceleration is calculated on the large lobe at end farthest from the neck of the comet. Note that gravity and cohesion act to hold the grain on the surface, but centripetal acceleration, the electrostatic force and gas drag act to detach the grain.

The cohesion is calculated as:

$$F_{co} = \frac{DS^2}{48B^2}\left(\frac{r_d}{2}\right) \tag{2}$$

based on the work by [1]. D is the Hamaker constant (assumed to be 4.3×10^{-20} J, as predicted for lunar regolith [15]), B is the diameter of an oxygen ion (1.32×10^{-10} m), and S is a nondimensional measure of the cleanliness of the regolith (estimated to be 0.75 in this work [15]).

Figure 1 shows that, in the absence of cohesion, grains smaller than 10s of centimeters would be likely to spontaneously detach from the surface of the comet. We note that if the grain charge is increased beyond 5V through tribocharging, then it may be easier to detach grains due to electrostatic forces, called electrostatic lofting.

3 Tribocharging of Dielectric Same-Material Grains

Lacks and Levandovsky previously proposed a theory for the triboelectric charging of dielectric granular mixtures [11]. In their theory, dielectric charging between grains of the same material occurs due to the transfer of electrons from high energy states on one grain to low energy states on a second grain. Additionally, only one electron was transferred between grains during collision. However, the number of electrons transferred should be dependent on the surface area of the contact between the grains. We have modified the theory of Lacks and Levandovsky to include this area-dependent charge transfer term and have also generalized the theory to arbitrary size distributions (rather than purely bidisperse mixtures) [16]. With these modifications to the theory and considering a bidisperse mixture, we find that average charge on the larger grains is given by:

$$Q* = \frac{(1 - sr^2)msr^2(m - d)}{(msr^2 + d)(dsr^2 + m)} \qquad (3)$$

Note that $Q*$ is non-dimensionalized by the charge of the high energy electrons at the initial state. m is the ratio of the total mass of the small grains divided by the total mass of the large grains ($m = m_2/m_1$), d is the ratio of the diameter of the small grains to the diameter of the large grains (always less than 1), $r = \left(2/(s(1 + d^3))\right)^{0.2}$ and $s = 1/4(1 + d)^2$.

A comparison of the resulting charge as a function of the grain size ratio d and the mixture mass ratio m is given in Figure 2. Figure 2 also shows the charging predicted by the Lacks and Levandovsky model for the same granular mixtures. Note that when the area-dependent charging is included, the predicted magnitude of charging decreases. Additionally, we note that for certain mixtures, the average charge on the large grains becomes negative. Prior experimentation has shown that large grains tend to charge positively, as is predicted by our model in most mixtures. However, there has not been a comprehensive experimental investigation of grain charging as a function of mixture properties, thus observation bias may have prevented detection of this phenomenon. We are currently developing an experiment to test the predictions shown in Figure 2 and described in [16].

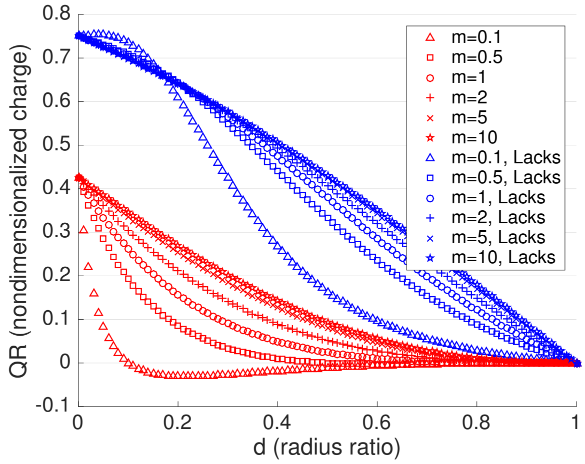

Figure 2. Nondimensionalized average charge on large grains of a bidisperse granular mixture as a function of the mixture mass ratio (total mass of small grains to total mass of large grains) and size ratio (small to large) predicted by the model by Carter and Hartzell [16] and compared to Lacks and Levandovsky [11]. Charge is nondimensionalized by the number of electrons initially in the high energy state on a single large grain.

The derivation of the average grain charge described here (and discussed in detail in [16]) is based on the theory that tribocharging between identical dielectric materials occurs when electrons trapped in high energy states on a grain are transferred to lower energy states on another grain. However, recent work by Waitukaitis *et al.*[17] measured high energy electrons through thermoluminescence and detected fewer high energy electrons than necessary to explain the tribocharging observed, weakening this hypothesized mechanism of triboelectric charging. Our model adds area-dependent charge transfer to the high energy electron transfer tribocharging model. The addition of area-dependent charge transfer changes predictions of the average polarity of tribocharged grains (specifically, it predicts that, in certain mixtures, large grains will charge negatively). It is significantly easier to experimentally measure the polarity of the net charge on a grain, as opposed to accurately measuring the exact charge on a grain. Thus, the model presented here provides a relatively simple test of the high energy electron transfer mechanism of tribocharging. If the predicted polarity is not observed experimentally, it will cast additional doubt on the hypothesis of high energy electron transfer mechanism of tribocharging. We are currently building an experiment to test this model.

Baytekin *et al.* have experimentally demonstrated that charge exchange between two polymer plates brought into contact occurs in patches (i.e. there are patches of positive and negative charge at scales of hundreds of nanometers across the plates) [18]. We expect that, on nanometer scales, there will be patches of positive and negative charge at the intersection surfaces of tribocharging dielectric regolith grains. Baytekin *et al* also show that, while the net charge on the polymer plates is relatively low, the charge density is higher than expected (1 elementary charge per 10nm^2) [18]. Note that the surface charge density in our model is currently a variable, although the model aims to predict the net charge on grains. Finally, Baytekin *et al* observed that material was transferred between the plates during tribocharging. While significant for many applications, we plan to experimentally test our tribocharging predictions with grains of the same material. Although there may be some small chemical differences between grains, we do not expect that material transfer will be a significant source of any observed tribocharging in our planned experiment.

4 Conclusion

We have presented a brief review of the forces active on the surface of an airless body, with specific emphasis on electrostatic forces. Figure 1 shows the relative magnitude of these forces for an example location on comet 67P/Churyumov-Gerasimenko. There is significant uncertainty about the electric potential of grains on the surface of an airless body. Additionally, the physics of charge exchange through tribocharging of dielectric grains of the same material is poorly understood. We present results of a theory for dielectric grain tribocharging (Figure 2) which we plan to experimentally test in the coming year. By coupling an improved model of granular tribocharging with our survey of forces on grains, we will be able to predict the possibility of electrostatic dust lofting as a result of spacecraft activities.

Acknowledgements

Thanks to Jessica Sunshine and Tony Farnham for their helpful discussion of the drag forces.

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