Electrostatic Lofting Conditions for Supercharged Dust

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Abstract

Electrostatic dust lofting may be a common occurrence on small bodies in the solar system, whereby the upward electrostatic force on a grain is able to overcome the surface gravity and cohesion binding it to the surface. This electrostatic lofting may serve to redistribute and transport dust across the surface of these bodies to produce features such as dust ponds and lineations found on Eros, or even to rid bodies of small particles completely. Classical models, which distribute charge evenly across a dust grain, have historically predicted electric field strengths that are insufficient to loft dust. However, recent studies have developed grain-scale charging models that account for the buildup of charge in the microcavities of regolith and assume unequal distribution of charge on a dust grain. These models predict electric field strengths orders of magnitude larger than classical models, which may explain how electrostatic dust lofting occurs on small bodies. In this paper, we compare the grain-scale supercharging models developed by Zimmerman et al. and survey how the different parameters affect grain charging—namely, charge separation, grain size, and dielectric breakdown strength. Furthermore, we investigate how each of the charging models can be used to bound initial condition requirements such as charge and velocity for dust lofting to occur on these small bodies. Initial condition requirements are examined for a range of grain sizes, regolith cohesive strengths, and small body sizes.

Unified Astronomy Thesaurus concepts: Asteroids (72); Asteroid surfaces (2209); Planetary surfaces (2113); Surface processes (2116)

1. Introduction

Electrostatic dust motion was first theorized when the Surveyor program observed the Lunar Horizon Glow, thought to be light scattering off of 10 μm particles just above the surface of the Moon (Rennilson & Criswell 1974). Dust grains are said to be electrostatically lofted when their electrostatic force overcomes the gravitational and cohesive forces binding them to the surface. Given that asteroids are less massive than the Moon, it was natural to extend the possibility of electrostatic dust motion to these bodies (Lee 1996). Observations of dust ponds on Eros, thought to be deposits of finer regolith at the bottom of craters, were postulated to be a product of preferential dust lofting and transport via electrostatic forces (Robinson et al. 2001). The electrostatic force required to loft particles is generated due to the constant bombardment of the surface regolith with ultraviolet radiation and solar wind particles. UV radiation on the dayside of a body causes photoemission and the surface tends to charge positively. As a result, the positively charged surface attracts electrons, causing a non-neutral region known as a plasma sheath to form above the surface. The unequal distribution of charge in the near surface space causes an electric field to be generated, which acts on the charged particles resting in the body’s surface regolith. In this way, particles build up charge and are acted upon by the plasma sheath’s electric field.

Numerical studies have also been conducted, such as that done by De & Criswell (1977) and Criswell & De (1977), that examined the electrostatic environment near the Lunar terminator region. This region, they believed, would be a likely scenario for dust lofting due to the larger electric fields predicted to exist there from the close proximity of sunlit and shadowed patches. They predicted fields on the order of 1000 V m⁻¹, which would be capable of electrostatically lofting particles from the surface; however, this field strength was taken as an upper limit as neutralizing currents and cohesion were not considered. More modern simulations have shown much more benign charging environments near the terminator (Poppe et al. 2012; Piquette & Horányi 2017). Scheeres et al. (2010) and Hartzell & Scheeres (2011) showed analytically that cohesion is a particularly important factor to consider for the smallest grains on asteroids. The importance of cohesion and its direct effect on grain lofting requirements was also shown experimentally by Hartzell et al. (2013), where piles of different sized grains were placed on a biased plate in plasma. Intermediate-sized grains were seen to preferentially loft due to their intermediate spot between smaller grains (cohesion dominated) and larger grains (gravity dominated). Colwell et al. (2005) numerically simulated 2D dust lofting on the surface of Eros by launching dust grains into a shadowed crater in the presence of a monotonically decreasing sheath model. From their investigation, they found that there was a net transport of dust grains into shadowed regions and even some particles were able to levitate just above the surface. Hughes et al. (2008) built on the results of Colwell et al. (2005) by simulating 3D dust launching into craters. In their simulation, gravity was held constant and the particle was given zero charge at simulation start. More recently, Hartzell & Scheeres (2013) used a non-monotonic plasma sheath developed by Nitter et al. (1998) to investigate equilibrium heights and charges of dust grains levitating above the surface of the Moon, Eros, and Itokawa.

While computational and experimental studies show electrostatic dust lofting to be a viable phenomenon for dust transport on small bodies, Hartzell & Scheeres (2011) showed that the electric field predicted to exist on the surface of small bodies is much smaller than that required to loft particles analytically,
particularly when accounting for regolith cohesion. Thus, some additional level of charging must occur to explain observed electrostatic dust motion. Recent studies examine charging at the grain scale and propose a new charge model which distributes charge unevenly on the surface of a grain, particularly in the microcavities between grains, as opposed to sharing charge equally across the grain surface (Wang et al. 2016). In these new models, the electric fields generated are predicted to be orders of magnitude larger than those predicted with classical models (Zimmerman et al. 2016), and experimental results even show that unexpectedly large negative charges are generated between grains which result in large grain–grain repulsive forces that lead to lofting (Wang et al. 2016). Such grain-scale charging models may provide the means by which we can generate and bound realistic conditions for electrostatic lofting to occur at small bodies.

In this paper, we compare the grain-scale charging models developed by Zimmerman et al. (2016) and investigate how each of these models can be used to bound initial condition requirements such as grain charge and the grain-scale electric field for electrostatic dust lofting to occur. Parameters such as grain size, regolith cohesion, primary body size, and the dielectric breakdown strength are examined. As a result, we find characteristic lofting speeds for particles as a function of particle size, cohesive forces, and local gravitational attraction. We focus on bounding these initial conditions using the maximum electric field in the gap between grains. These bounds are useful as they can constrain the degree to which dust migration can occur on a body, and predict whether a body will preferentially shed dust grains less than a characteristic size.

The paper is structured as follows. In Section 2, the three main models developed by Zimmerman et al. (2016) for dust charging are reviewed. Section 3 provides details into the investigation of dust lofting requirements, namely, defining maximum gap electric field conditions and bounding initial lofting speeds from the surface. Additionally, this section

Figure 1. Left: scenarios of unequal charge distribution on dust grains at the surface. Red patches represent areas with positive charge (electron emitting surfaces), while blue patches represent areas with negative charge (electron receiving surfaces). Right: two negatively charged grains interacting near the surface. Forces acting on the dust grains are assumed to be collinear in this study, with the electrostatic force acting upward ($F_{elec}$) and the gravitational ($F_{grav}$) and cohesive ($F_{coh}$) forces acting downward. Note that depending on which model is used, the right grain can be positive (photoemission only) or negative (solar wind only and photoemission with solar wind). The photoemission with solar wind charging model is depicted here.

Figure 2. Idealized parallel surfaces charging on adjacent grains. Note that the solar wind ions are modeled as a (monoenergetic) beam incident only on the right wall, while the solar wind electrons and photoelectrons are omnidirectional (have an isotropic thermal distribution) (Zimmerman et al. 2016).
examines the effect of charge separation and the dielectric breakdown strength on the charging characteristics of dust grains. Finally, Section 4 details the implications of these results.

2. Grain-scale Supercharging Models

The surfaces of asteroids are constantly bombarded by ultraviolet radiation and the solar wind plasma, causing their regolith grains to charge from photoemission, solar wind electron and ion collection, and secondary electron emission. While grain charging has been studied extensively, the details of how individual dust grains charge and interact electrostatically with neighboring regolith grains at the grain scale has only recently been characterized (Zimmerman et al. 2016). Here we review the models developed therein.

Zimmerman et al. (2016) gives a few scenarios of dust grain interactions at the grain scale that could lead to differential charging. See Figure 1 for reference.

A. Direct illumination of the topmost grain.
B. Direct illumination of small patches on the second layer of grains.
C. Illuminated patch adjacent to a shadowed facet.
D. Two illuminated facets adjacent to one another.

Parameters affecting the rate of electric field generation include the characteristic scale length $L$ of charge separation, grain charge $Q_{gr}$, grain mass $m_{gr}$, kinetic energy of the charged particles $U$, the emission flux $J$, the electric constant $\varepsilon_0$, and grain permittivity.

For the remainder of the analysis in this paper, we will consider adjacent grains in scenario C, as is done in Zimmerman et al. (2016). Grains that charge negatively and repulse each other may lead to electrostatic lofting (shown in the right plot of Figure 1). Here we conservatively assume the forces are collinear with gravity and cohesion to simplify the problem and bound lofting requirements. Figure 2 shows the simplified geometry of two adjacent grains, whose charge areas are parallel. The sign of the charge density will depend on the charge model used. For the photoemission model, the sunlit side constantly emits photoelectrons and gains a net positive charge, while the shadowed side collects an equal and opposite charge. This separation of charge produces an attractive electric field. However, for both the solar wind only model and the combined photoemission with solar wind model, the grain patches both charge negatively, as will be shown below. In these cases, the resulting negative-charge buildup on both patches is repulsive and may cause grains to electrostatically loft from the surface.

Note that Zimmerman et al. (2016) assumes a charge separation of $L = r_d/10$ and a charged patch area of $L^2$. We will use the numbers referenced in Zimmerman et al. (2016) in any computations executed below, unless otherwise noted.

The first model Zimmerman et al. (2016) develops is the photoemission-only case, which assumes a Maxwellian distribution of electrons. For this case, the charge density changes as

$$\dot{\sigma} = J_{pe} \exp\left(\frac{-\Delta \sigma}{2\Sigma_p}\right), \tag{1}$$

where $J_{pe} = 4 \times 10^{-6}$ A m$^{-2}$ is the photoelectron flux, $\sigma$ is the grain charge density, and $\Sigma_p = \varepsilon_0 U_{th}/eL$ is the photoelectron charge density. Examining this photoemission-only model, the total surface charge could theoretically grow without bound and is only limited by the half rotation period of the primary body. While this model is too idealistic, it is a good place to build from.

To limit the charge growth in a realistic way, the effect of electrical conductivity of the grains is added. Draining of the surface charge through the grain is represented as a current density $J_{\varnothing} = \varnothing E_{int}$ where $\varnothing$ is the conductivity of the grain and $E_{int}$ is the electric field inside the grain. As a result, the conductivity enters the charge equation as a sink term, and the modified photoemission with conductivity charging model is as follows:

$$\dot{\sigma}_R = J_{pe} \exp\left(\frac{-\Delta \sigma}{2\Sigma_p}\right) - \frac{\varnothing}{2\varepsilon_0} \Delta \sigma, \tag{2a}$$

$$\dot{\sigma}_L = -J_{pe} \exp\left(\frac{-\Delta \sigma}{2\Sigma_p}\right) + \frac{\varnothing}{2\varepsilon_0} \Delta \sigma, \tag{2b}$$

Figure 3. Charge density (left) and charge density rate (right) as functions of time for a 22 $\mu$m grain using the photoemission with conductivity model.
Note that under the assumption of equal and opposite charge on the two sides of the grains (representing a parallel plate capacitor), the net electric field outside the capacitor is zero. Thus, there is no external electric field to drive charge away from either grain. This implies that the two neighboring grains will continue to charge up indefinitely. This is a flaw in the Zimmerman et al. (2016) paper. Because we do not use the photoemission-only model in calculating lofting requirements, but instead only use it to build up development of the charging models, the conductivity sink term will remain in the equations presented above.

Integrating these equations over time with each grain starting at zero charge, Figure 3 illustrates the charge densities and charge density rates of both grains as a function of time. Here we see that the grains charge equally in magnitude but oppositely in sign—the right grain attains a positive charge density, while the left grain attains a negative-charge density. Note that this would result in an attractive electrostatic force between grains.

Next, Zimmerman et al. (2016) extends the idealized scenario to solar wind bombardment and derives the following charging equation accounting for solar wind and conductivity (without photoemission):

\[
\Delta\sigma = \Delta\sigma_R - \Delta\sigma_L = 2J_{pe} \exp\left(-\frac{\Delta\sigma}{2\Sigma_e}\right) - \frac{\vartheta}{\varepsilon_0} \Delta\sigma. \quad (2c)
\]

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Here we see that both the right and left grains charge negatively, resulting in a repulsive electrostatic force. This type of repulsive force is what can lead to grain lofting. We also see that the charging rate between the two plates comes to an equilibrium near $10^2$ s (see Figure 8 also).

Finally putting everything together, the wall-charging equation for simultaneous photoemission and solar wind bombardment with conductivity is

$$\Delta \sigma = 2J_e \exp \left( -\frac{\Delta \sigma}{\Sigma_e} \right)$$

$$+ 2J_{pe} \exp \left( -\frac{\Delta \sigma}{2\Sigma_{pe}} \right) - \frac{\theta}{\varepsilon_0} \Delta \sigma,$$

$$\Delta \sigma = -J_e \exp \left( -\frac{\Delta \sigma}{\Sigma_e} \right) - J_{pe} \exp \left( -\frac{\Delta \sigma}{2\Sigma_{pe}} \right) + \frac{\theta}{\varepsilon_0} \Delta \sigma. \quad (4c)$$

Starting with zero charge on both grains and integrating these equations over time, Figure 5 illustrates the charge densities and charge density rates of both grains as a function of time. Note in Figure 5 that the absolute value of the charge density is plotted. At small times, the charge density of the right grain (in blue) is positive as photoemission acts to eliminate electrons from that grain. The downward spike indicates the time at which the right grain begins to charge
negatively as the solar wind charging dominates. Both the right and left grains in this model end up with negative-charge densities as time increases. Again we see that charging reaches an equilibrium prior to 10^2 s.

Both grains charging negatively is an interesting and nonintuitive result that appears to be an artifact of the unique interplay between photoemission and solar wind charging in the microcavities between grains, as modeled by Zimmerman et al. (2016). Performing a simple integration of the \( \dot{\sigma} \) Equations 4(a) and (b) over time for the same 22 \( \mu m \) grain, Figure 6 illustrates the current density components over time. This enables us to directly see how the different particle populations contribute to the charge densities of each grain over time.

For the left grain, solar wind electrons (red) and photoelectrons (yellow) contribute to negative-charge buildup, while conductivity (purple) inhibits it. For the right grain, the solar wind electrons (red) and conductivity (purple) contribute to negative-charge buildup, while the photoelectrons (yellow) and solar wind ions (blue) inhibit it. Here we see that while the photoemission component dominates in the beginning, its significance diminishes over time. This is because photoemission reaches an equilibrium more quickly than solar wind electrons in this model. The solar wind electron component stays relatively stable throughout the entirety of the integration and ends up dominating as time increases. These observations are also reflected in the left plot of Figure 5 when the right grain charge changes sign from positive to negative. The sunlit grain charges negatively. Physically, this appears to be an artifact of the grain-scale supercharging model developed by Zimmerman et al. (2016).

For each of the models above, the electric field in the gap between grain patches is given by

\[
E(t) = -\frac{\Delta \sigma(t)}{2\varepsilon_0},
\]

where \( \Delta \sigma(t) \) is the time-varying charge density difference between the two walls and \( \varepsilon_0 \) is the permittivity of free space. While the photoemission (without conductivity) case is
unbounded, all of the other charge density rate equations \((\Delta \dot{\sigma})\) given above will reach an equilibrium due to the conductivity sink term. This maximum charge density difference (related to the maximum gap electric field) can be solved for numerically by setting the charging rate \(\Delta \dot{\sigma} = 0\) for a given grain radius and solving for the resulting charge density difference \(\Delta \sigma\). These maximum gap electric field conditions are discussed in detail in Section 3.1. Figure 7 shows the maximum gap electric field strength for the charge models discussed above. Note that various breakdown strengths are denoted on the plot. The effect of these breakdown levels will be discussed in more detail in Section 3.5 below.

Next we plot the associated charge densities on the right and left grain patches when the gap electric field is maximum for each of the three models. The results are plotted as a function of grain radius in Figure 8. Note here that the photoemission-only model produces an attractive electric field (grains are oppositely charged), while the solar wind only model and the photoemission with solar wind model produce repulsive electric fields (grains are like charged). Also, as the grain size increases, the charge density at the maximum gap electric field condition approaches an asymptote.

Additionally, we can compute the time dependence of the electric field experienced by one wall as a result of the other wall by integrating any of the charge density equations above and dividing by the permittivity of free space \(\varepsilon_0\):

\[
E(t) = \frac{\sigma(t)}{2\varepsilon_0}.
\]  

Here the right wall experiences an electric field of \(E = \sigma_L/2\varepsilon_0\), due to the charge density of the left wall, while the left wall experiences an electric field of \(E = \sigma_R/2\varepsilon_0\) due to the charge density of the right wall. Note the important difference between Equations (5) and (6). In Equation (5), a test particle placed between the two charged walls experiences an electric field dependent on the electric field of both walls \((\Delta \sigma)\), while in Equation (6), each wall only experiences an electric field from the opposing wall \((\sigma)\) and is not influenced by its own electric field.

We can also compute the time rate of change of the grain charge using the assumed charge patch area:

\[
Q(t) = \sigma(t)L^2.
\]  

### Table 1

| Body Name | Mass \(\times 10^{10} \text{ kg}\) | Mean Radius m | Surface Gravity \(\text{m s}^{-2}\) | Surface Escape Speed \(\text{cm s}^{-1}\) |
|-----------|---------------------------------|---------------|------------------|-----------------|
| Itokawa   | \(3.51\)                        | 173           | \(7.8 \times 10^{-5}\) | 16              |
| Bennu     | \(7.329\)                       | 245           | \(8.1 \times 10^{-5}\) | 20              |
| Ryugu     | \(4.50 \times 10^{11}\)        | 460           | \(1.4 \times 10^{-4}\) | 36              |
| Eros      | \(6.687 \times 10^{15}\)       | 7311          | \(8.3 \times 10^{-3}\) | 11              |
| Moon      | \(7.34767 \times 10^{22}\)     | 1737.7        | \(1.6 \times 10^{-2}\) | 2376            |

**Note.** Parameter references for Itokawa (Fujikawa et al. 2006), Bennu (Lauretta et al. 2019), Ryugu (Hasegawa et al. 2008; Watanabe et al. 2019), Eros (Yeomans et al. 2000; Zuber et al. 2000), and the Moon (Smith et al. 1997; Wieczorek et al. 2006).
This further enables calculation of the electrostatic force felt between the adjacent grains:

\[ F_{\text{elec}}(t) = Q(t)E(t) = \sigma(t)L_{\text{rd}}^2 \sigma_e(t) \frac{\sigma_e(t)}{2\varepsilon_0}. \]  

Equating the electrostatic force to various external forces, Zimmerman et al. (2016) numerically computes exposure times required to overcome various levels of cohesion and gravity on different primary bodies for each of the models above. The models dominated by photoemission reach maximum gap electric field strength within \(10^2\) s or less, while the solar wind only model reaches maximum gap electric field strength within \(10^3\) s or less (Zimmerman et al. 2016). Thus, grains undergoing this grain-scale supercharging reach their maximum gap electric field strengths relatively quickly—within minutes rather than hours. This suggests that grain charging is not limited to typical asteroid rotation periods, which are on the order of a few hours or longer. Instead grain-scale supercharging happens much more quickly, enabling grains to reach lofting requirements theoretically at many points throughout the local day, depending on local surface illumination conditions.

To verify that these models did indeed reach their maximum charge densities quickly, we integrated the charge densities over time for four different grain sizes: 1, 10, 100, and 1000 \(\mu\)m. The results are shown in Figure 9. As expected, maximum charge values are reached quickly—roughly within \(10^2\) s for all four cases. These results align with those presented in Zimmerman et al. (2016) for exposure times.

From our evaluation here of the charging models presented in Zimmerman et al. (2016), we are able to conclude that (1) this more realistic grain-scale model of charging leads to a maximum gap electric field strength as a function of grain size, and (2) the time to reach this maximum gap electric field strength is relatively short when compared to typical asteroid rotation periods. This leads us to investigate in the following section how each of the charging models discussed above can be used to bound initial condition requirements such as charge and velocity for dust lofting on small bodies in the solar system. Specifically we examine simplified models for Bennu, Itokawa, Ryugu, Eros, and the Moon. Relevant parameters for each of the bodies are given in Table 1.

### 3. Lofting Conditions for Supercharged Grains

In this section, we compare the supercharging models described above and solve for the maximum gap electric field conditions. We also develop a method of calculating dust grain initial conditions required for lofting for a variety of surface conditions. We then examine the sensitivity that charge separation has on dust grain charging, as well as the dielectric breakdown strength of the material.

#### 3.1. Maximum Gap Electric Field Conditions

Here we examine the two charging models which lead to a repulsive electrostatic force between grains—solar wind only (Equation (3)) and photoemission with solar wind (Equation (4))—over a range of grain sizes, regolith cohesions, and primary body sizes. For the analysis in this subsection, we assume a grain charge separation of \(L = r_{\text{rd}}/10\), following Zimmerman et al. (2016) for consistency.

First we solve for the maximum gap electric field as a function of grain size, assuming the idealized geometry shown in Figure 2. Solving for the value of charge density \(\Delta \sigma\) when the charge density rate \(\Delta \dot{\sigma}\) goes to zero, we find the trends shown in Figure 10.

From Figure 10, we can see that the maximum charge density difference decreases as grain size is increased. Assuming a charging area of \(L^2\), we can then compute the associated charge a grain could acquire at these conditions using Equation (7), \(Q_{\text{max}} = \sigma_{\text{max}} L^2\). These charge values for both models and both grains are plotted over a range of grain sizes in Figure 11. Note here that the individual charge densities are integrated forward in time until the maximum

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**Figure 12.** The electrostatic force associated with the maximum gap electric field over a range of grain sizes for two different charging models—solar wind only in a dashed-dotted black line and combined photoemission with solar wind in a solid black line. A range of gravitational forces is plotted in various shades of solid teal, while a range of cohesive forces is plotted in various shades of dashed purple.
charge density difference is reached. As the grain size increases, this maximum gap charge difference occurs closer to the initial charge density difference. This explains why the trend lines in Figure 11 become more jagged at larger grain radii—the maximum charge density difference is less well defined for larger grains.

Overall we see that the associated charge increases for increasing grain radii. For micron-sized particles, the maximum grain charge is found to be on the order of $10^{-17}$–$10^{-16}$ C, depending on which model is used. Again, it is also important to note the timescale over which these charge densities occur. From Section 2, we know that supercharging rates are maxed out very quickly, on the order of $10^2$ s or less. Thus, we can assume that grains reach these charge values quickly. As a result, those that are able to overcome their local gravitational and cohesive environments may be able to loft at multiple points throughout the day.

### 3.2. Conditions for Electrostatic Lofting

Next we look at the conditions under which dust grains loft, namely, how the electrostatic force compares to the forces of gravity and cohesion holding the grain to the surface. We note that at the moment just prior to lofting, the electrostatic force will exactly equal the combined cohesive and gravitational forces (see Equation (9)). Using this knowledge, we can solve for different lofting requirements:

$$F_{\text{elec}} = F_{\text{coh}} + F_{\text{grav}}.$$  

(9)

Recall from Equation (8) that we can calculate the electrostatic force using the charge densities of both walls ($\sigma_L$ and $\sigma_R$) and

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**Figure 13.** Cohesive strength (at maximum gap electric field condition) as a function of grain size. Left: values shown for two different charging models—solar wind in red and combined photoemission with solar wind in yellow—for grains on a single primary body, Ryugu. Right: values shown for grains on a variety of primary bodies—Bennu in blue, Itokawa in red, Ryugu in yellow, Eros in purple, and the Moon in green—for a single charging model (combined photoemission with solar wind).

**Figure 14.** Electrostatic accelerations associated with the maximum gap electric field over a range of grain sizes for two different charging models—solar wind only in a dashed–dotted black line and combined photoemission with solar wind in a solid black line. A range of gravitational accelerations is plotted in various shades of solid teal, while a range of cohesive accelerations is plotted in various shades of dashed purple.
the charged patch area \( L^2 \). The electrostatic force associated with the maximum gap electric field conditions for each of the three dust grain sizes. The maximum condition velocities use asteroid Ryugu as the primary body. Recall that these maximum condition solutions require selection of a primary body (see gravity dependence in Equation (17)).

where \( m_d \) is the grain mass, \( g \) is the gravitational acceleration at the surface, \( r_d \) is the grain radius, and \( \rho_d \) is the grain density (assumed to be 2.4 g cm\(^{-3}\) to mimic the grain density of Bennu (Lauretta et al. 2019). The cohesive force is calculated using

\[
F_{\text{coh}} = \sigma_y A = 2\pi r_d^2 \sigma_y
\]

from Sánchez & Scheeres (2014), where \( \sigma_y \) is the cohesive strength of the regolith (given in pascals) and \( A \) is the contact area of the grain with the regolith. We assume that half the grain surface area is in contact with the cohesive matrix of smaller grains described in Sánchez & Scheeres (2014).

From Figure 12, we see that a limit exists, past which certain grain sizes will not be able to overcome the local cohesive or gravitational forces experienced at the surface. Any grain experiencing gravitational or cohesive forces with magnitudes above \( 10^{-9} \) N would not be loftable.

Solution of the associated electrostatic force (Figure 12) also bounds the cohesive strength a grain can overcome on a given small body. Thus if we insert the necessary parameters at the maximum gap electric field condition into Equation (9), we can solve for this associated cohesive strength:

\[
\sigma_{\text{coh}} = \frac{F_{\text{elec,max}} \Delta \sigma - F_{\text{grav}}}{2\pi r_d^2}
\]

\[
= \frac{\sigma_t \sigma_d \left( \frac{L}{r_d} \right)^2}{4\pi \varepsilon_0} - \frac{2}{3} \rho_d g r_d
\]

\[
= \frac{\sigma_t \sigma_d}{400 \pi \sigma_0} - \frac{2}{3} \rho_d g r_d. \quad (12)
\]

Recall here that \( \sigma_t \) refers to the cohesive strength of regolith, while \( \sigma \) refers to the charge density of a dust grain. The cohesive strengths associated with the maximum gap electric fields are plotted against grain size in Figure 13.

The plot on the left gives the cohesive strengths for the two different charging models on a single primary body (Ryugu) at...
separation of L photoemission with solar wind model for our analysis. Recall that grains from the surface. In this section, we will use the combined requirements for a range of grain sizes and surface properties.

In the next section, we will develop a method of computing accelerations above the maximum electrostatic accelerations are not loftable. Furthermore we see that electrostatic and cohesive accelerations decrease with increasing grain radii. This means that smaller grains are able to overcome larger cohesion strengths near 0.5 Pa. Whereas grains in the tens of microns range can only overcome cohesive forces with strengths near 5 Pa, surface separation as a result. For instance, micron-sized grains can overcome cohesive forces with strengths near 5 Pa, whereas grains in the tens of microns range can only overcome cohesion strengths near 0.5 Pa.

In this section we have developed a method of solving for maximum gap electric field conditions, while the plot on the right shows the cohesive strengths for five different primary bodies using a single charging model (combined photoemission with solar wind). Overall we see that the associated cohesion decreases with increasing grain size, which is primarily due to the charge density product term σ\(_L\)R\(_d\) (both decrease with increasing grain size). Note also that the data terminates when the gravity term is large enough so that the cohesion goes to zero. This termination point bounds not only the effect of cohesion on dust lofting, but also of grain radius and primary body size, thus providing clarity on the unique interplay of the three parameters on dust lofting requirements.

We can also examine the same comparisons for accelerations that we did for forces by dividing by the grain mass. These accelerations are shown in Figure 14. Recall we are using spherical grains with a grain density of 2.4 g cm\(^{-3}\). Again, we note that any grains with combined gravitational and cohesive accelerations above the maximum electrostatic accelerations are not loftable. Furthermore we see that electrostatic and cohesive accelerations decrease with increasing grain radii. This means that smaller grains are able to overcome larger cohesions and also experience a larger initial acceleration at surface separation as a result. For instance, micron-sized grains can overcome cohesive forces with strengths near 5 Pa, whereas grains in the tens of microns range can only overcome cohesion strengths near 0.5 Pa.

In this section we have developed a method of solving for maximum gap electric field conditions for a variety of grain-scale charge models and used these conditions to bound lofting requirements for a range of grain sizes and surface properties. In the next section, we will develop a method of computing lofting ejection speeds for these grains. Because the combined photoemission with solar wind model is the most complete of the charging models examined, we will use this model in the remainder of our analysis presented below.

### 3.3. Initial Velocity Calculation

Using the accelerations shown in Figure 14, we can directly calculate initial velocity conditions for electrostatic lofting of grains from the surface. In this section, we will use the combined photoemission with solar wind model for our analysis. Recall that lofting of a grain occurs when the electrostatic force is greater in magnitude than the combined gravitational and cohesive forces holding the grain down to the surface. Here we assume the forces are aligned, as shown in Figure 1, which provides a conservative estimate for our results.

At time \(t_{0-}\) just before separation from the surface, the grain feels a net acceleration of zero. The upward electrostatic force exactly cancels out the downward cohesive and gravitational forces:

\[
\sum F(t_{0-}) = F_{\text{elect}} - F_{\text{coh}} - F_{\text{grav}} = 0. \tag{13}
\]

At time \(t_{0+}\) just after separation from the surface, the grain will feel a net upward acceleration from to the loss of cohesion (due to the surface contact with the cohesive matrix being broken):

\[
\sum F(t_{0+}) = F_{\text{elect}} - F_{\text{grav}} = m_d a. \tag{14}
\]

Because the electrostatic and gravitational forces remain unchanged and only the cohesive force disappears with separation, the net upward acceleration is equal to the acceleration associated with the cohesive force that was previously binding the grain to the surface:

\[
a_{\text{coh}} = \frac{F_{\text{coh}}}{m_d} = \frac{3}{2} \frac{\sigma_y}{\rho_d r_d}. \tag{15}
\]

Assuming supercharging only affects grain motion within a few radii of the surface and conservatively assuming a constant acceleration over this small distance, we can solve for the initial velocity of the grain once it breaks its cohesive bonds:

\[
v_0 = \sqrt{2a_{\text{coh}}(x_0)} = \sqrt{\frac{3}{2} \frac{x_0 \sigma_y}{\rho_d r_d}}. \tag{16}
\]

Here we use the coefficient \(x\) to denote the number of grain radii over which the constant acceleration acts. For comparison, Figure 15 shows how the initial velocity would change for varying distances over which the supercharging acts (1 \(r_d\), 2 \(r_d\), 3 \(r_d\)) for a range of grain sizes on asteroid Ryugu.
Examining the initial velocity requirement at maximum gap electric field conditions, we find the following relation with particle size:

\[
v_{0,\text{max} \Delta \sigma} = \sqrt{\frac{3 \sigma_{y,\text{max}} \Delta \sigma}{\rho_d}}
\]

\[
= \sqrt{\frac{3 \sigma_l \sigma_R}{4 \pi \varepsilon_0 \rho_d} \left( \frac{L}{r_d} \right)^2 - 2 x g g_f}. \quad (17)
\]

Note here that the \( \sigma_{y,\text{max} \Delta \sigma} \) term will also have dependence on the grain radius through the separation distance \( L = r_d/10 \), specifically in the \( \Sigma_{\text{pe}} \) and \( \Sigma_{\text{e}} \) terms within the charge density rates \( \sigma_l \) and \( \sigma_R \).

From Figure 15, we see that increasing the distance over which the supercharging acceleration occurs will increase the initial velocity of the grain slightly; however, overall the values are comparable for each of the different distances. It is also interesting to note that in our formulation, the initial velocity calculation is independent of grain size, except when computing the initial velocity at maximum gap electric field conditions (i.e., placement of the stars in Figure 15). Note also that the maximum gap electric field conditions require selection of a primary body, as evidenced by the gravity dependence of Equation (17). For the sake of Figure 15, we chose Ryugu as our primary body. Given the results of Figure 15, we move forward using a distance of two grain radii (\( x = 2 \)) over which the supercharging force acts.

Looking at the \( v_{0,\text{max} \Delta \sigma} \) term in greater depth, we can separate this quantity into two separate parts:

\[
v_{0,\text{max} \Delta \sigma} = \sqrt{\frac{3 \sigma_l \sigma_R}{200 \pi \varepsilon_0 \rho_d}} - 4 g g_f
\]

\[
= \sqrt{\max^2 - 4 g g_f}
\]

\[
= \max \sqrt{1 - \frac{4 g g_f}{\max^2}}. \quad (18)
\]

Here \( \max \) represents the maximum initial velocity a lofted grain will experience without consideration to gravity:

\[
\max^2 = \frac{3 \sigma_l \sigma_R}{2 \pi \varepsilon_0 \rho_d} \left( \frac{L}{r_d} \right)^2
\]

\[
= \frac{3 \sigma_l \sigma_R}{200 \pi \varepsilon_0 \rho_d}, \quad (19)
\]

while the remaining factor is a correction term that maintains a dependence on gravity. By separating the initial velocity into these two separate parts—one independent of gravity—we can generalize our initial velocity findings to a variety of small bodies. In fact, this \( \max \) quantity is the largest contributor to the initial velocity and is plotted as a function of grain size in Figure 16.

Here we see that the initial velocity decreases as grain size is increased, indicating that it should be easier for smaller grains
to be lofted to escape. For Ryugu, the local escape speed from the surface is on the order of 0.4 m s$^{-1}$ ignoring rotation (which will decrease it). Thus, the smallest grains are susceptible to being directly ejected. We note that once a particle is lofted, additional forces such as solar radiation pressure are also effective in stripping away smaller particles.

Next, we examine the second part of Equation (18), specifically looking at when $1 - \frac{4\pi\sigma}{V_{\text{max}}}$ goes to zero. This represents a grain that has acquired sufficient charge to exactly cancel gravity and cohesion, and as a result, experiences zero initial velocity. Using this relation, we can solve for the maximum gravity allowable for a lofted dust grain. In this way we can constrain the size of primary body that grains of a given size could loft from

$$g_{\text{max}} = \frac{V_{\text{max}}^2}{2x_d} = \frac{V_{\text{max}}^2}{4\rho_d}$$  \hspace{1cm} (20)

This maximum gravity value is plotted in Figure 17 as a function of grain size. Here we notice that the maximum gravity becomes quite large, making this a nonessential quantity and implying that the lofting speed is most strongly a function of the $V_{\text{max}}$ parameter.

In this section, we have developed a method of computing the initial speed with which lofted dust grains come off the surface. Additionally we have computed this velocity at the maximum gap electric field condition, which bounds grain

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**Figure 22.** A breakdown strength of $10^7$ V m$^{-1}$ is used as an upper bound on grain charging. Left: the associated grain charge densities when the electric field strength is maximum for three different models. The photoemission-only model is plotted in blue, the solar wind only model is plotted in red, and the photoemission with solar wind model is plotted in yellow. Right: ejection speed $V_{\text{max}}$ as a function of grain radius.

**Figure 23.** Electrostatic force over a range of grain sizes for two different charging models—solar wind only in a dashed–dotted black line and combined photoemission with solar wind in a solid black line. A range of gravitational forces is plotted in various shades of solid teal, while a range of cohesive forces is plotted in various shades of dashed purple. Here a breakdown strength of $10^7$ V m$^{-1}$ is used as an upper bound on grain charging.
lofting initial conditions. We have also generalized the results to be independent of gravity for application to a wider range of bodies in the solar system. In the next sections we will survey how certain parameters in the charging models affect grain charging.

### 3.4. Effect of Charge Separation

In this section we examine how the characteristic scale length of charge separation $L$ affects grain charging. Note that this study uses the combined photoemission with solar wind charging model.

Assuming again that the charge area on each grain is directly related to the charge separation through $A = L^2$, we vary the characteristic scale length $L$ and compute the maximum charge density difference over a range of grain sizes. Figure 18 gives the results for three different lengths: $r_d$, $r_d/10$, and $r_d/100$. In the left plot of Figure 18, we see that as the characteristic scale length for charge separation is decreased, the maximum charge density difference increases. Assuming that the charge area is related to the scale length as $A = L^2$, it is unsurprising that the maximum grain charge decreases with decreasing scale length, as shown in the right plot. Thus, grains with smaller charge separations will reach higher maximum charge density differences but acquire lower overall grain charges.

Solving for the associated electrostatic force, Figure 19 shows the results. We see that smaller charge separation yields smaller electrostatic forces. This means that grains with smaller charge separations will be more limited in the surface conditions they can overcome, when compared to grains with larger charge separations. As a result, grains with smaller charge separations will not be able to overcome the same cohesions as grains with larger charge separations, which will limit their upward lofting speed (see also Figure 16). This effect, however, diminishes as grain size increases.

Next we look at the associated initial velocity as a function of grain size for the different charge separations shown in Figure 20. We see that the associated lofting velocity decreases as the grain size increases. Additionally, as the charge separation distance decreases, the initial velocity also decreases. This is expected, as we noted from Figure 19, grains with smaller charge separations will experience smaller electrostatic forces and will only be able to loft from regolith with lower cohesive strengths as a result. This is due to the fact that the initial velocity is directly related to the cohesive force (Equation (16)). However, this relationship fades as the grain size is increased, at which point the various charge separation distances produce equivalent results.

Overall we find that more compactly situated grains (those with smaller charge separation) will reach higher maximum charge densities but lower overall grain charges. The effect of this on lofting means that grains with smaller charge separations will experience smaller electrostatic forces and will be more limited in the surface conditions they can loft from (lower cohesive strengths), when compared to grains with larger charge separations. However, the effect of charge separation on the ability of grains to loft diminishes as grain size is increased.

### 3.5. Effect of Breakdown Strength

In this section, we examine how the dielectric breakdown strength affects charging behavior. Dielectric breakdown is an intrinsic property of the grain material. Breakdown occurs when the electric field inside the grain becomes large enough that the grain begins to act as a conductor and current is transferred from one wall to the other instantaneously. Breakdown strengths between $10^6$ and $10^8$ V m$^{-1}$ (Budenstein 1980; Frederickson et al. 1986; Sorensen et al. 1999) are cited as realistic bounds for our study here. From Figure 7 above, we can see that a breakdown level of $10^8$ V m$^{-1}$ should not affect the supercharging values. However, next we will analyze how breakdown levels of $10^6$ and $10^7$ V m$^{-1}$ affect grain charging and lofting.

Looking first at a breakdown strength of $10^7$ V m$^{-1}$, we plot the maximum gap electric field strengths in Figure 21. Note that because the electric field inside the grain is equal and opposite to that in the gap between grains, this analysis can be performed using the gap electric field calculations. From this plot we see that only the photoemission and photoemission with solar wind models are affected by the breakdown strength for grain sizes below 2 $\mu$m in radius.

Next we plot the charge density associated with the maximum electric field and the resulting ejection speed in Figure 22. Note that only the ejection speeds for the solar wind only and the combined photoemission with solar wind models are given since those are the only models which can result in lofting. For the photoemission-only model in the left plot, the charge density magnitudes are decreased as a result of the breakdown strength (compare with Figure 8), and so the resulting attractive electrostatic force would be weaker. For the photoemission with solar wind model, we see that at small grain radii, accounting for dielectric breakdown results in a positive charge on the right grain, which produces an attractive (not repulsive) electrostatic force with the negatively charged left grain. Thus, the dielectric breakdown level affects the ability of the photoemission with solar wind model to loft grains at small radii and places a lower limit on the loftable grain size in these charging conditions. Looking at the right plot of Figure 22, this means that the ejection speeds associated with these non-lofting grain conditions (at small grain radii) are not applicable, and thus are not plotted.
Next we examine how the electrostatic force is affected when dielectric breakdown is accounted for in Figure 23. Here we see that the smaller grains affected by the dielectric breakdown will experience smaller electrostatic forces. As discussed in the previous plots, this means that the cohesive strengths that these grains can overcome will decrease.

Next looking at a breakdown strength of $10^6 \text{ V m}^{-1}$, Figure 24 illustrates the maximum electric field strengths for the three models. Here we see that all three models are affected by the dielectric breakdown for grain sizes up to several microns in radius for the solar wind model and up to several tens of microns in radius for the other two models.

Next we examine the charge densities of the grains and the ejection speeds in Figure 25. For the photoemission-only model, we see that the charge density magnitude is decreased for a wider range of grain sizes. While this model always results in oppositely charged grains and thus an attractive electric field (no grain lofting), the overall field magnitude is decreased as a result of the breakdown strength. For the combined photoemission with solar wind model, we again see that dielectric breakdown results in a population of smaller grains that are not loftable. Up to around 30 $\mu$m, the grains are oppositely charged and so experience an attractive electrostatic force. For the solar wind only model, the grains are negatively charged and always experience a repulsive electrostatic force. However, dielectric breakdown lowers the magnitude of charge on the grains, which results in a lower overall electrostatic force. From Figure 26, we see that this affects the cohesive strength a grain is able to overcome.

Looking at the right plot of Figure 25, we can see that there exists a range of grain sizes larger than those that are not loftable and smaller than those unaffected by the breakdown.
strength (less than $7 \, \mu m$ for the solar wind only model and between 30 and $40 \, \mu m$ for the photoemission with solar wind model) whose ejection speed is affected by the breakdown strength. For these grains, their ejection speed decreases due to dielectric breakdown, and thus these grains may not be able to overcome the same cohesive strengths as if dielectric breakdown is neglected. Figure 26 also illustrates this point.

Overall dielectric breakdown acts to place a lower limit on the grain size that is loftable using the photoemission with solar wind model. For all three models, dielectric breakdown acts to limit grain charge and results in weaker electrostatic forces, which limits the cohesive strengths that grains can overcome.

4. Conclusions

While electrostatic dust lofting has been theorized as a mechanism of dust transport across and off the surface of small bodies, determining the conditions under which dust is able to loft has been the topic of study for many years. Electric field predictions from classical models are not able to account for the forces necessary to separate dust grains from the surface, particularly when accounting for cohesion. However, new charged patch models, which account for buildup of charge in the microcavities between individual dust grains and the unequal distribution of charge on a dust grain, predict much higher electric field strengths that are able to account for the difference between classical model predictions and experimental observations of dust lofting events.

Here we examine these new grain-scale supercharging models (Zimmerman et al. 2016) and are able to use them to bound the initial conditions required for dust grain lofting. Specifically, we solve for maximum gap electric field conditions over a range of grain sizes to bound local surface conditions required for lofting. We are not only able to solve for the associated grain charge, but also the associated maximum cohesive strength a grain can overcome. Furthermore, we use this information at the maximum gap electric field condition to compute the initial speed with which lofted grains are ejected from the surface. Given the escape speed and rotation rate of an asteroid, this information can be used to predict which grain populations are the most mobile and which may have been stripped away completely from the surface over the natural evolution of the body. By separating the initial velocity computation into two separate parts, we are able to generalize our results to a wider range of bodies due to the independence of one parameter to gravity. Overall, we have developed a simpler method of generating initial conditions for lofted grains while using supercharging models to account for grain-scale electric field generation.

Additionally, through examination of different variables affecting grain-scale charging—such as grain size, charge separation, regolith cohesion, and primary body size—we are able to better understand and bound how dust grains of different sizes and in different environments will be affected. Namely, we find that grains with smaller charge separations (perhaps more compactly situated on the surface) will reach higher maximum charge densities, but lower overall grain charges. As a result these grains will be more limited in the surface conditions they are able to loft from. We also examined the effect that the dielectric breakdown strength plays in grain charging. In particular, dielectric breakdown appears to place a lower limit on the size of grains that can be electrostatically lofted by limiting charge buildup.

Overall the analysis conducted in this paper provides a more complete understanding of the grain-scale supercharging models presented in Zimmerman et al. (2016), the different parameters affecting grain charging, and how these models can be used to bound electrostatic lofting requirements for dust grains on small bodies in the solar system.

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