



# Unconventional Surface Charging Within Deep Cavities on Airless Planetary Bodies: Particle-In-Cell Plasma Simulations

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**Key Points:**

- Unconventional current balance is established between solar wind ion and electron at the bottom of deep cavities on the Moon and asteroids
- Cavity bottom surface could have significant positive potentials that are comparable to the kinetic energies of solar wind ions
- Photoelectrons no longer promote positive charging by themselves but rather relax the positive potentials at the cavity bottom

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## Unconventional Surface Charging Within Deep Cavities on Airless Planetary Bodies: Particle-In-Cell Plasma Simulations

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**Abstract** Surface charging properties of a nonconducting surface that has a deep cavity and is in contact with the solar wind plasma are investigated by means of the particle-in-cell plasma simulations. The modeled topography is an abstract representation of deep depressions found on the irregular surfaces of solid planetary bodies. The simulations have revealed unconventional charging features in that the cavity bottom is charged up to positive values even without any electron emission processes such as photoemission, provided that the surface location is accessible to a portion of incoming solar wind ions. The major driver of the positive charging is identified as drifting ions of the solar wind plasma, and an uncommon current ordering where ion currents exceed electron currents is established at the innermost part of the deep cavity. This also implies that the deep cavity bottom may have a positive potential of several hundred volts, which is similar in magnitude to the kinetic energy of an ion drift motion. The present study also clarifies the role of photoelectrons in developing the distinctive charging environment inside the cavity. The photoemitted electrons can no longer trigger positive charging at the cavity bottom, but rather exhibit the effect of relaxing positive potentials caused by the solar wind ions. The identified charging process, which is primarily due to the solar wind ions, is localized at the depths of the cavity and may be one possible scenario for generating intense electric fields inside the cavity.

**Plain Language Summary** Kinetic plasma simulations suggest that unconventional surface electrical charging conditions develop within deep cavities on the Moon and other airless planetary bodies, which are directly impacted by the solar wind. Due to their aligned directions of motion, ions are more likely to reach the innermost part of such deep cavities than thermal electrons without being lost at the cavity sidewall. The ion current at the bottom of a cavity with a high depth-width aspect ratio tends to exceed the electron current. This generates a significant positive potential, similar in magnitude to the kinetic energy of solar wind ions and independent of the work done by photoelectron emissions. This positive charging process, primarily due to solar wind ions, is localized at depths in the cavities and may result in strong electric fields on the dayside of the Moon and asteroids.

### 1. Introduction

A solid surface that is in contact with a plasma collects electric charges of impinging electrons and ions. In general, due to the higher differential influx of electrons than that of ions, the surface gets charged negatively, that is, acquires a negative potential with respect to the environment (Whipple, 1981). This potential field exerts a repulsive force for approaching electrons and restrains further inflow of thermal electrons. The equilibrium (or floating) potential is eventually reached when the positive and negative charge inflows are balanced; that is, the net current flow into the surface becomes zero. This concept of current balance holds also in the presence of additional current components that are caused by emission processes of charged particles. The charging process (e.g., Garrett, 1981) and its feedback to plasma environment, such as the formation of sheaths and presheaths (e.g., Robertson, 2013; Scheiner et al., 2015), have been investigated extensively. In space applications, the understanding of charging processes has been developed through long-standing studies of spacecraft charging as well as probe measurements (e.g., Fahleson, 1967; Garrett & Whittlesey, 2000).

The surface charging is a significant research area also for the physics of airless, solid planetary bodies in the solar system, such as the Moon and asteroids (Manka, 1973; Stubbs et al., 2014; Zimmerman et al., 2014). This is because charging possibly leads to electrostatic transport of charged dust grains on their surfaces (Nitter et al., 1998; Stubbs, Vondrak, & Farrell, 2007). Such natural bodies covered with nonconducting regolith layers exhibit manifested differential charging depending on both space-environmental and surface conditions. On-orbit observations and theoretical predictions have shown that the darkside and terminator

regions of the Moon have negative surface potentials, whereas the dayside surface has positive potentials (Farrell et al., 2010; Halekas et al., 2002, 2008; Stubbs, Halekas, et al., 2007). In light of the fact that an ambient plasma by itself tends to make solid surfaces charge negatively, it is acknowledged that the positive equilibrium potentials on the day side are made possible by the aid of negative charge transfer from the surface to space through electron emission processes such as photoemission (e.g., Freeman & Ibrahim, 1975; Stubbs et al., 2014).

Although the idea of photoemission-led charging is widely accepted as an “averaged picture” of forming positive potentials on the dayside, some surface geometric features may open up interesting possibilities for localized but unconventional scenarios of charging. This aspect is of particular importance for solid natural bodies in space because numerous variations of surface geometries with different spatial scales can be found. There are plenty of rocks, boulders, and craters with various shapes. Recent on-orbit observations have also revealed many pits of around 10 m in width and depth (Wagner & Robinson, 2014). In smaller scales, regolith particle layers can form wide variety of surface geometries such as bumps and dips. The present study aims to demonstrate that a plasma condition relevant to the solar wind exhibits an ability of locally producing positive potentials by itself, even without photoemission (or any other electron emission processes), when a certain class of surface geometry, a cavity, is considered. The targeted cavity is the one with an opening to the upper space, and thereby precipitating plasma particles are partially accessible to it. Such surface structures in a decameter scale were identified as “vertical holes” or “pits” on the Moon (Haruyama et al., 2009), and its electric environment was examined by means of numerical plasma simulations (Miyake & Nishino, 2015). In smaller scales, complex pileup of small rocks and regolith particles reduces to an irregular surface. Some local geometries of the surface can be categorized into cavities. The electrostatic aspects related to such small cavities have been one of the outstanding issues of great interest (Orger et al., 2019; Wang et al., 2016).

The charging processes of irregular surfaces have been investigated via numerical and ground-experimental approaches in efforts to advance electrostatics on the Moon and other small bodies. On their dayside surfaces, the presence of impact craters or boulders gives rise to differential solar UV irradiation and even local shadows. These features lead to nonuniform potential distribution over the surface (e.g., Farrell et al., 2007; Poppe et al., 2012; Wang et al., 2019; Zimmerman et al., 2011, 2012). The shadow can be also regarded as a region of limited access for a solar wind plasma. The plasma expansion theory has been applied to interpret the extent of plasma incursion beyond a shadow boundary (Farrell et al., 2007). Electrostatic structures in even smaller scales, as those of regolith particles, are also of particular interest. In such scales, disability of the Debye shielding leads to more intense electrostatic fields, which is believed as one of important factors for mobilization and breakdown of charged regolith particles (Zimmerman et al., 2016).

We numerically work on electric potential profiles and their associated motions of solar wind plasma particles in the vicinity of a cavity. The model cavity is assumed to have a depth-width aspect ratio ranging from 1 to 6, which is greater than typical values for impact craters. The investigations are focused on loss processes of thermal electrons and ballistic ions at the solid sidewalls of the cavity. In such a situation, ions tend to penetrate deeper into the cavity than electrons, and a current balance condition will be altered significantly at the bottom of the cavity. We will demonstrate that this feature is feasible, by means of three-dimensional particle-in-cell (PIC) simulations with plasma conditions relevant to the solar wind (Miyake & Nishino, 2015). As the orthogonal grid system is employed in the simulator in use, we study a rectangular-shaped cavity to exploit its resolution ability. Despite this artificial shape, we will show that physical insight abstracted from the simulation results can constitute one aspect of charging evolving on natural small bodies. We note that edge effects caused by the shape is also interesting in itself, but are beyond of the scope of the present study.

This study is organized as follows. Section 2 describes the numerical simulation model. The major simulation results are presented and discussed in Section 3. We first focus on the most simplified situation of cavity surface charging by only imposing a solar wind downflow to its surface. The obtained result indicates that positive potentials are formed at the cavity bottom even without any electron emission processes. The electrostatic structure and the associated particle motions are investigated to elucidate the charging mechanism. We subsequently introduce the effects of photoelectron emission and discuss a role of photoelectrons in altering a current balance condition inside the cavity. Section 4 discusses some important aspects for applications of the identified charging mechanism to electrostatics on the Moon and other airless small bodies. Finally, Section 5 concludes with a summary of the main findings and provides perspectives of further studies.

## 2. Numerical Experiment Setup

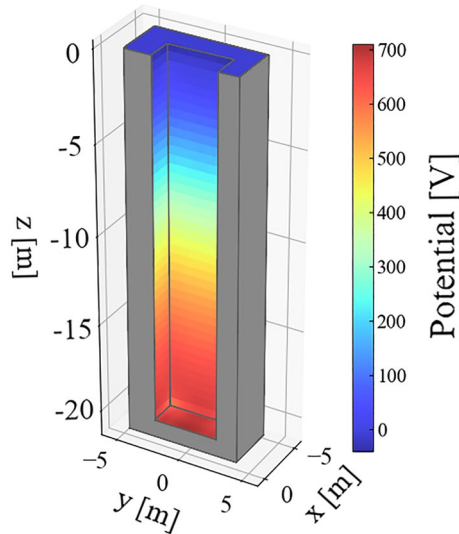
Plasma environment near a solid surface with a single cavity is modeled by using an in-house full-particle plasma simulator: EMSES (Miyake & Usui, 2009). The simulation tool is based on the standard electromagnetic PIC method (Birdsall & Langdon, 2018; Hockney & Eastwood, 1981), whereas its basic functionality is designed for addressing plasma interactions with solid inner boundaries. PIC describes a plasma as a bunch of charged macroparticles, each of which represents many real plasma particles. The computational particles are initially distributed over a computational domain except for the interior of solid bodies, and their motions are represented by Newton's equations of motions. Electromagnetic field components are defined discretely on computational grid points. Note that since the present study focuses on electrostatic structures near a solid surface with a cavity, we solve only Poisson's equation for electrostatic potential to compute particle pushing fields. The field and particle data sets are then updated simultaneously by employing the finite difference scheme.

An important feature of EMSES is capability of incorporating solid objects into computations. The object surfaces are represented as internal boundaries, which satisfy appropriate conditions for both particles and field components. Once a charged particle collides with a solid structure, the particle is regarded as sticking to the surface and no longer processed as an "active particle." EMSES keeps monitoring particle positions to detect sticking particles and eliminate them from a list of active particles. Electric charges carried by colliding particles are deposited onto a surface. Particle emission processes such as photoemission are numerically processed as particle release from a surface. EMSES loads new particles with appropriate positions and velocities complying with the physical processes in consideration. In simulating photoemission with EMSES, it is normally assumed that the energy distribution of emitted population is a single Maxwellian, and their angular distribution of emission shall follow a cosine function.

The computational kernel of EMSES is parallelized with the Message Passing Interface (MPI) based on the block domain decomposition. To avoid possible computational efficiency degradation, EMSES adopts a dynamic load-balancing algorithm referred to as OhHelp (Nakashima et al., 2009). With the OhHelp algorithm, a simulation space is divided into as many subdomains as the number of MPI processes, but up to two decomposed subdomains are assigned to each process. In other words, each subdomain is handled by multiple processes. This allows the computational load for subdomains having particles more than the per-subdomain average to be shared among multiple processes, which equalizes per-MPI-process loads in association with both particle and field data sets. Scalable parallel PIC computations regardless of particle distributions are achieved with the benefit of this sophisticated auxiliary algorithm (Miyake & Nakashima, 2013). This aspect is of particular importance in addressing the physics of body-plasma interactions because such phenomena may cause outstanding inhomogeneity of particle distributions.

A box-shaped simulation space is partitioned into spaces occupied by plasma particles and a solid matter, and their interface is configured in such a way that it shapes a plane surface and a single deep depression (i.e., cavity). Considering planetary bodies covered with highly resistive regolith particles (e.g., Olhoeft et al., 1974), the solid surface simulated herein is simply modeled as a perfect insulator. This indicates that electric charges of particles hitting the surface are accumulated in situ. We take the  $z$ -axis of the Cartesian coordinates in the direction of elevation. The (plane) surface of the planetary body is then defined as the reference of the  $z$  coordinate. The lower limit of the simulation space is located at  $z = -30$  m. The total volume of the simulation space is  $16 \times 16 \times 128$  m<sup>3</sup>. The entire space is discretized with uniform grids of 0.5 m. The square-shaped cavity is assumed to have dimensions of a fixed width  $W = 5$  m and a variable depth  $D$  ranging 5–30 m. For convenience, we denote the  $z$ -coordinate of the cavity bottom as  $z_b$ . A key geometric parameter is the depth-width aspect ratio of the cavity defined as  $R_{D/W} = D/W$ , which is varied within 1–6 in the present study. Note that the model cavity has a spatial scale comparable to the Debye length  $\lambda_D \sim 10$  m in the solar wind plasma. Such a cavity may be larger than what can be found typically on natural planetary bodies in space. The size parameters were chosen such that we can exploit the sweet spot of the numerical scheme in terms of available computational resources and spatial resolutions gained by them. Since a target of broader interest would be smaller cavities practically, we later on discuss applicability of the obtained insight to such smaller sizes.

The solar wind plasma is initially distributed in the simulation space and also continuously loaded from its top and lateral edges. The bulk velocity  $v_b$  and the unperturbed density  $n_0$  of the solar wind are given as 400 km/s and 5/cc, respectively. We assume that simulated electrons and ions are in an isothermal condition, and their



**Figure 1.** Three-dimensional view of the surface potential distribution obtained from the simulation run with the cavity depth-width aspect ratio  $R_{D/W} = 4$  and a vertical solar wind incidence ( $\theta = 0^\circ$ ). In the simulation, the photoelectron emission is intentionally excluded to clarify an unconventional current ordering between solar wind electrons and ions developed at the cavity bottom.

temperature is given as 10 eV. The combination of the chosen parameters provide the associated velocity ratio  $v_{te} : v_b : v_{ti} = 42.9 : 12.9 : 1.0$ , where  $v_{te}$  and  $v_{ti}$  represent the thermal velocities of electrons and ions, respectively. Later on, we will show that the given ordering  $v_{te} > v_b > v_{ti}$  is another key factor for unconventional charging properties inside the cavity. To elucidate physical processes related to charging, this study carries out simulations with increasing complicating factors in a step-by-step fashion. We first present the results of simulations that intentionally exclude photoemitted electrons. This basic exercise is followed by the results of calculations that take into account the effects of photoelectrons.

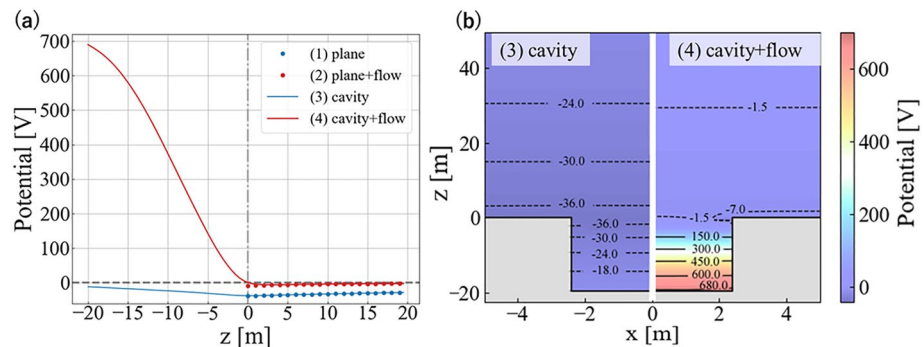
Based on the experimental setup described above, we calculated the charging process of the model cavity until the steady-state solutions were obtained. Figure 1 illustrates a result obtained from the simulation runs, which is highlighted in the present study. The figure displays a three-dimensional view of surface potential for  $R_{D/W} = 4$ . The representative result clearly shows significant potential enhancement in the innermost part of the cavity. The following section explores an unconventional mechanism underlying in the cavity charging. For reasons of space constraints, the two-dimensional profiles shown hereafter are displayed with the aspect ratio changed from the physical one.

### 3. Results

#### 3.1. Electrostatic Structure Near a Cavity

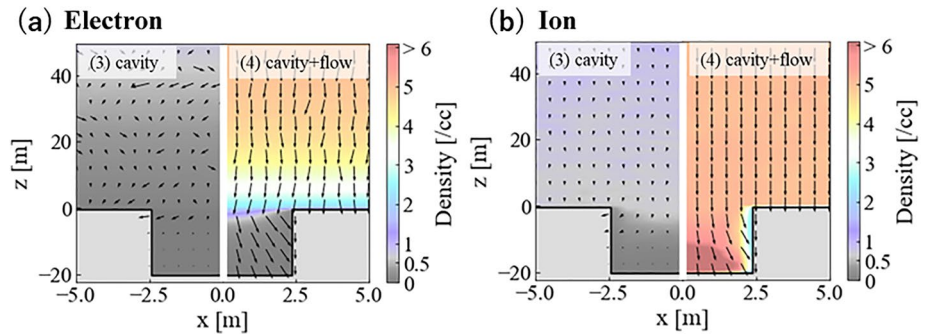
PIC computations addressed here are focused on the surface charging inside the cavity due to solar wind inflow. To this end, we intentionally exclude any electron emission processes here. Although the photoelectron emission is in fact essential in considering dayside surface charging, lessons from this basic investigation will clarify a number of dominant physical processes, which is key to a distinctive charging mode evolved at the cavity surface. This section presents the results obtained in four different simulation configurations: (1) plane (i.e., no cavity) without flow, (2) plane with flow, (3) cavity without flow, and (4) cavity with flow. For runs (3) and (4), we adopt a fixed cavity aspect ratio  $R_{D/W} = 4$ , and the dependency on this important parameter is studied in the subsequent section.

Figure 2 shows the spatial profiles of electric potential near the surface. Figure 2a displays the potential distributions along  $z$ -axis penetrating the center of the  $xy$  plane ( $x = y = 0$  m). The ranges  $z < 0$  and  $z > 0$  correspond to the inside and outside of the cavity, respectively. The potential values at  $z = -20$  m correspond to surface



**Figure 2.** Spatial profiles of electric potential obtained in four different simulation configurations: (1) plane without flow, (2) plane with flow, (3) cavity without flow, and (4) cavity with flow. For runs (3) and (4), two-dimensional profiles are also displayed in the right panel. The cavity aspect ratio  $R_{D/W} = 4$  is used in the simulations (3) and (4). One-dimensional potentials (a) are plotted along  $z$ -axis placed at the center of the cavity. Two-dimensional profiles (b) show potential structures in an  $xz$  plane cutting the center of the cavity. Note that the panel (b) is displayed not in a physical aspect ratio but in an adjusted ratio  $z/x \sim 10$  for visibility. (See the scales on the vertical and horizontal axes.)





**Figure 3.** Plasma density and flux vector with a cavity ( $R_{D/W} = 4$ ). Electron (a) and ion (b) density and flux vector with (right half) or without (left half) the bulk flow, respectively. The vector lengths are proportional to the magnitude (in a logarithmic scale) of the local fluxes.

potentials at the cavity bottom. For the cases with the cavity, the two-dimensional profiles are also displayed in Figure 2b, the left and right halves of which correspond to the stationary and flowing plasma cases, respectively. All potential values are referenced at  $z = \sim 100$  m above the plane surface.

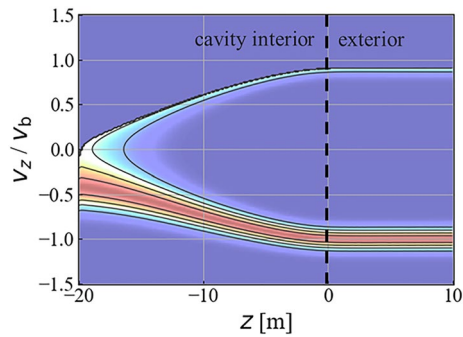
The potential profiles from the simulation without the cavity (the dotted plots in Figure 2a) conform to the classical floating potential theory for a surface in plasma (e.g., Whipple, 1981). Attributed to the higher differential flux for electrons than ions, the surface attains a negative potential such that the current balance between electrons and ions, that is,  $J_i - J_e = 0$ , is established at each position, where  $J_i$  and  $J_e$  denote the ion and electron current densities, respectively. With a plasma bulk motion, the surface potential becomes less negative. This is a consequence of increased  $J_i$ , while  $J_e$  is less affected by the bulk motion due to the large thermal velocity of electrons. Analytical estimations of  $J_i$  and  $J_e$  give flat surface potential values of  $-38$  and  $-8.0$  V for cases (1) and (2), respectively. The simulations are in reasonable agreement with the estimates, except for a small deviation resulting from the finite size of the simulation domain not being sufficient to cover a long presheath extending above.

The presence of the cavity alters the situation drastically. This is in particular pronounced for the case with the downward plasma bulk motion (i.e., the solid red line in Figure 2a and the right half of Figure 2b). Although the potential near the cavity aperture is comparable to that without the cavity, it continues to increase with depth, eventually reaching  $+700$  V at the cavity bottom. The high potential is not limited to the center of a cavity floor but covers an entire floor as well as sidewalls near the floor, as indicated in the two-dimensional plot. Such extraordinary charging is not identified for the stationary plasma case, even with the cavity; the negative potential relaxes with depth and settles to about  $-10$  V at the bottom.

The outlined result exhibits a number of key features associated with charging of inner-cavity surfaces. One distinctive aspect of the result is the positive potential, which the cavity floor attains in an equilibrium state. This is in contrast to common knowledge that a solid surface in contact with an electron-ion plasma is ordinary floating at a negative potential. The high-degree charging is also an outstanding feature. The potential value  $+700$  V is comparable to the kinetic energy of individual protons  $+840$  eV associated with their bulk motions. Such quantitative association suggests a leading role of an ion bulk motion as a determining factor of an electrostatic energy acquired by the innermost part of the cavity. This speculation is supported by the fact that the case without bulk motion shows no manifestation of such positive charging. To clarify the underlying mechanism of the key result, we next see density and velocity field profiles obtained for the cases with the cavity.

Figure 3 shows the electron and ion density profiles on the plane cutting the center of y-axis, on which the velocity vector field of each species is overlaid with arrows. The left and right halves of each panel correspond to the results for stationary and flowing plasma cases, respectively. The flowing plasma case exhibits a pronounced difference between the ion and electron densities. The electron density declines drastically inside the cavity, whereas the ion density keeps an unperturbed level halfway down the cavity, and even gets enhanced in its innermost part.

Considering that  $v_{te} > v_b > v_{ti}$  holds with regard to the velocities involved, the density feature is interpreted as consequences of diverging motions of electrons into the solid walls of the cavity and less deflected trajectories of ions due to the appreciable bulk velocity. Such an orbit-mechanical picture is supported by the comparison



**Figure 4.**  $z$ - $v_z$  phase plot of ions, measured along the vertical axis intersecting the center of the cavity bottom, obtained from simulation run (4). The domains  $z < 0$  and  $z > 0$  correspond to the interior and exterior of the cavity, respectively.

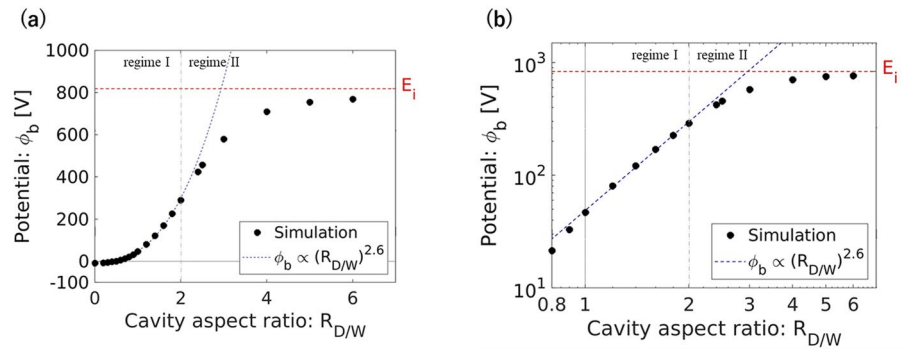
to an uncharged surface. Such unusual current ordering triggers positive charging even if, in principle, there are no electron emission processes. The potential difference between the aperture and bottom of the cavity can be comparable to kinetic energy of ion bulk motions, although the potential difference is strongly dependent also on cavity geometries. Associated intense electric field plays an essential role in regaining ion-electron current balance, through repelling some fraction of incoming ions as well as drawing electrons into the cavity floor before they stick to the sidewalls.

Ion-driven charging identified herein is conditioned not only on the presence of a space enclosed by solid walls (like a cavity) but also on an appreciable  $v_b$  speed exceeding  $v_{ti}$  because the velocity ordering  $v_{te} > v_b > v_{ti}$  is the key to unbalanced sticking rates between electrons and ions at cavity sidewalls. This is evident also from simulation run (3) with a stationary plasma (Figure 3), in which the density and velocity profiles of ions are less differentiated from those of electrons inside the cavity. With nearly zero or small  $v_b$ , ion motions tend to have divergent nature like electrons and are more likely to stick to the sidewall of the cavity. We note that even when considering a stationary plasma, ions near a surface should attain a certain bulk velocity toward the surface due to acceleration within sheath and presheath regions. Such bulk motion energy makes the ions a bit more accessible to the innermost part of the cavity and results in marginal rise of potential, as outlined in Figure 2a.

An intriguing effect suggested by the identified charging is ion backscattering due to the highly positive potential inside the cavity. Our simulations actually capture the feature of such backscattering in simulation run (4). Figure 4 shows the  $z$ - $v_z$  phase plot of ions measured along the vertical axis intersecting the center of the cavity bottom. The precipitating ion population is seen in the negative  $v_z$  domain. Inside the cavity ( $z < 0$ ), the deceleration of the descending flow gets pronounced, which is the consequence of the intense upward electric field. Such a decelerated flow is clearly correlated with the density enhancement identified in the lower half of the cavity (Figure 3b). Despite the deceleration, the majority of the ions reach the cavity bottom surface ( $z = -20$  m) whereby they contribute to the positive charging. Meanwhile, a small portion of the ions are electrostatically reflected before reaching the bottom and form an ion upflow. This implies that the positive charging associated with deep cavities may contribute in part to ion reflection or backscattering, the latter being expected when the cavity bottom has an irregular shape. Since the reflected ions originally constitute a low-energy component of incoming ions, their mean kinetic energy should be somewhat smaller than that of solar wind ions. In fact, in the present simulation, the kinetic energy of the reflected ions is roughly 80% that of the precipitating ions.

### 3.2. Dependence on a Cavity Aspect Ratio

Given that the aforementioned interpretation for the unconventional charging holds, the bottom potential should have a strong dependence on the depth-width aspect ratio  $R_{D/W}$  of the cavity. Figure 5 examines such dependence by plotting potentials measured at the center of the cavity floor,  $\phi_b$ , as a function of  $R_{D/W}$ . (The condition  $R_{D/W} = 0$  corresponds to a case only with a plane surface, i.e., no cavity.) With introducing the cavity and increasing  $R_{D/W}$ ,  $\phi_b$  turns into positive and rises monotonically up to 800 V. The trend reflects the fact that the degree of difference between electron and ion motions, in terms of their sticking rates at the sidewall and the resulting accessibility



**Figure 5.** The dependence of the cavity bottom potential on the depth-width aspect ratio derived from a number of simulation runs, excluding photoemission effects. The vertical (potential) axis of the figures is scaled in (a) linear and (b) logarithm. The potential value is measured at the center of the cavity floor. Note that in practice, the charging state transitions smoothly from regime I to II, and there is no clear boundary between the two.

to the bottom, is more pronounced for deeper cavities. The examination also reveals the asymptotic behavior of  $\phi_b$  as a function of  $R_{D/W}$ . For  $R_{D/W} \leq 2$  (referred to as regime I hereinafter),  $\phi_b(R_{D/W})$  is found to be the best fit with a power function of  $(R_{D/W})^{2.6}$ , as confirmed in the double logarithmic plot (Figure 5b). For  $R_{D/W} > 2$  (regime II, in the same manner),  $\phi_b$  begins to saturate and asymptotically approaches a positive potential  $\sim 800$  eV. This potential is comparable to the ion kinetic energy  $E_i = 840$  eV for the drift speed  $v_b = 400$  km/s. It is insightful to study separately how current balance conditions are established in these two regimes.

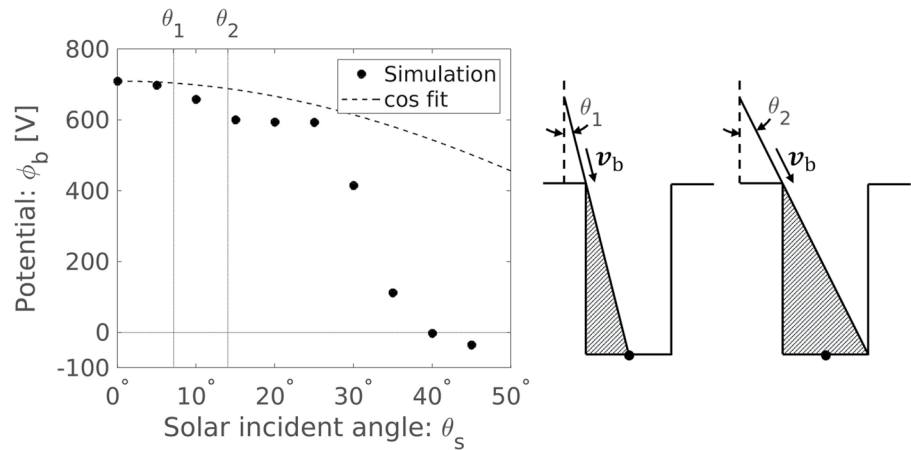
As the ion current  $J_i$  inherently tends to be greater than the electron current  $J_e$  in the depths of the cavity, either the ion current must be suppressed or the electron current must increase to restore the current balance at the cavity bottom. The positive potential developed at the cavity bottom, and the associated upward electrostatic field, should exert one or both of these two effects. In regime II where  $\phi_b \sim E_i$ , a potential barrier formed inside the cavity is capable of repelling incoming ions. In fact, we have already verified this effect in Figure 4. Therefore, the decline of  $J_i$  plays a major role in establishing current balance in this regime. This is in contrast to an object in an electron-ion plasma with a negative floating potential, which maintains current balance by repelling electrons.

In regime I where  $\phi_b \ll E_i$ , an ion-repulsive force alone is insufficient to recover current balance, because ions, which individually have energies comparable to  $E_i$ , are hardly repelled by the forces. That is, the ion current  $J_i$  is not substantially reduced much from  $J_{i0}$  that is the current value to an uncharged surface. Instead, electron attraction due to the positive bottom surface potential plays a major role in establishing current balance. A shorter cavity transit time leads to a lower proportion of electrons sticking to the cavity sidewall, which in turn increases the proportion of electrons attaining the cavity bottom. Consequently, the electron current  $J_e$  becomes greater than  $J_{e0}$  to an uncharged surface. This enhanced  $J_e$  can balance with the ion current  $J_i \sim J_{i0}$ , resulting in forming the equilibrium potential.

To test this physical scenario, let us consider the “free fall” motion of an electron where the only force acting on it is a vertical (upward) electric field. For further simplicity, we assume that the vertical electric field is spatially uniform, that is,  $E_c = \phi_b/D$ . The cavity transit time  $\tau_e$ , for which the electron reaches the cavity bottom, is expressed as  $\tau_e = D\sqrt{2m_e/e\phi_b}$ , under an assumption that the initial downward velocity of the electron is sufficiently small and negligible compared with its final speed after acceleration. This transit time is used to calculate traversing distances  $v_x\tau_e$  and  $v_y\tau_e$  in the  $x$  and  $y$  directions, respectively, for an electron with constant transverse velocities  $v_x$  and  $v_y$ . Since  $|v_x|\tau_e > W/2$  or  $|v_y|\tau_e > W/2$  indicates that such electrons are not accessible to the center of the cavity floor, we now obtain the maximum transverse velocities  $(v_{x,\max}, v_{y,\max}) = (1/R_{D/W})\sqrt{e\phi_b/8m_e}$  for electrons that are accessible to the center of the floor without being captured by the sidewall. These velocities (i.e.,  $\pm v_{\{x,y\},\max}$ ) are used as lower and upper limits of integral range of the velocity distribution function (in  $v_x$ - $v_y$  space) to evaluate  $J_e$  at the cavity bottom.

As long as the ion current is virtually unchanged by the charging, that is,  $J_i \sim J_{i0}$ , in regime I, its counterpart  $J_e$  should be also constant and  $J_e \sim J_{i0}$ . This indicates that  $v_{\{x,y\},\max}$  should be invariant in that regime. It follows that the cavity bottom potential should have a dependence of  $\phi_b \propto (R_{D/W})^2$  so that  $v_{\{x,y\},\max}$  remains unchanged. While





**Figure 6.** The dependence of the cavity bottom potential on the solar wind incident angle  $\theta$ . The plotted potential values are the ones measured at the center of the cavity floor.

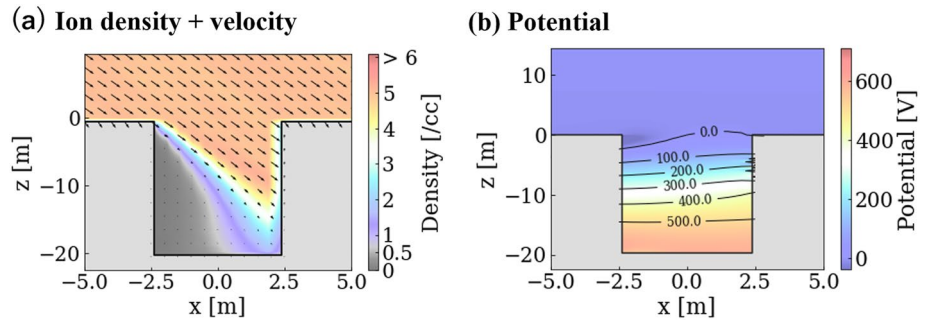
the discussion so far is very simplistic, it is a relatively good representation of the fact that the cavity bottom potential is well characterized by power functions of a dimensionless parameter, that is, the depth-width aspect ratio  $R_{D/W}$  of the cavity. These arguments also provide further evidence that the main physical root of the unconventional charging phenomena presented herein is the shadowing effect by the cavity sidewall, which scrapes off the diagonally incident component of electrons in their velocity space. In the course of the above discussion, we use a number of crude assumptions such as that electrons have zero downward velocity at the inlet of the cavity, which is, of course, not practical. Finite initial downward velocities would enhance  $J_e$  and then reduce  $\phi_b$  from the simple estimate discussed above. The deviation would be more pronounced for small  $R_{D/W}$  and less so for large  $R_{D/W}$  values. This may be the reason behind the simulation results that  $\phi_b$  scales with a greater power (i.e., 2.6) of  $R_{D/W}$  than the factor of 2. More rigorous treatments for the assumptions used in the analysis would be available and will be presented in the future studies.

### 3.3. Solar Wind Irradiation Angle Dependency

Irradiation angle of the solar wind is also an important factor. Figure 6 examines this aspect by showing  $\phi_b$  for solar irradiation angles  $\theta$  varying through  $0^\circ$ – $45^\circ$ , in which the cavity aspect ratio remains unchanged as  $R_{D/W} = 4$ . As  $\theta$  increases within  $0^\circ < \theta < 25^\circ$ ,  $\phi_b$  declines gradually but remains at several hundreds of volts. The small decline in  $\phi_b$  is attributed to a reduction in the vertical component of a bulk velocity due to increased inclination of the flow. Reminding that  $R_{D/W} = 4$  is within regime II, the reduction in kinetic energy of ion vertical motions results in the decline in  $\phi_b$ .

The potential decreases sharply for  $\theta > 25^\circ$  and turns into negative at  $\theta > 40^\circ$ . It is speculated that the sharp  $\phi_b$  decline implies that the cavity floor gets inaccessible to solar wind ions coming at further oblique angles. For  $\theta > 30^\circ$ , we confirmed that an ion flow majorly hits the sidewall of the cavity and cannot reach the cavity bottom, although not shown herein. It should be recognized, however, that the center of the cavity bottom is already in solar eclipse by the sidewall, even at much lower angles such as  $\theta = 10^\circ$ . Thus, maintaining a fairly high  $\phi_b$  in  $10^\circ < \theta < 25^\circ$  suggests that ion trajectories are not straight but deflected inside the cavity.

Ion deflection is actually identified in the present simulations. Figure 7a displays ion density and velocity field profiles simulated for  $\theta = 20^\circ$ . The ion flow expands into a shadow region, which enables a fraction of ions to reach the cavity bottom. Several physical processes may be possible to interpret the expansion of ions. The action of an ambipolar electric field is one of possible explanations. In this scenario, ion expansion into the plasma void region is preceded by that of electrons led by pressure gradient forces. It is known that the expansion rate in the case is characterized by an ion acoustic speed (e.g., Samir et al., 1983). The role of this ambipolar electric field was often referred to as a primary factor in a quasi-neutral plasma expansion into permanently shadow regions on the Moon (e.g., Zimmerman et al., 2011). Note that while the above expansion mechanism is based on the condition that the core plasma is quasi-neutral, the plasma entering the cavity this time is in somewhat a different



**Figure 7.** Two-dimensional profiles of (a) ion density and flux vector and (b) potential in case of an oblique solar wind incidence ( $\theta = 20^\circ$ ). The vector lengths are proportional to the magnitude (in a logarithmic scale) of the local fluxes.

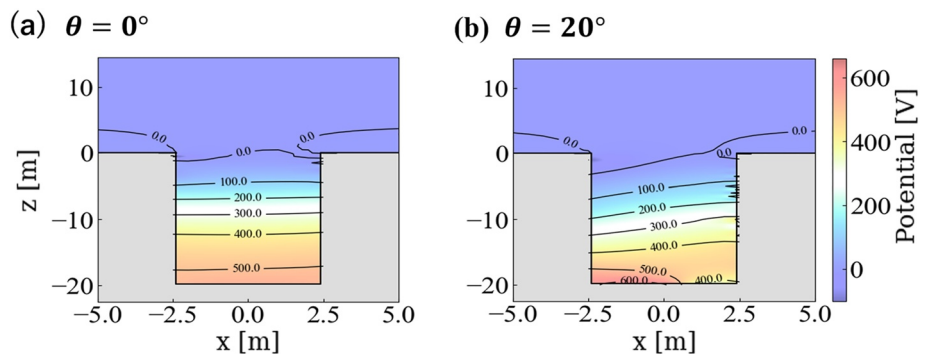
condition. Since electrons in the cavity are significantly reduced by the sidewall, the quasi-neutral condition is broken and ions behave like an unneutralized beam. The beam divergence mechanism should cause the ions to expand even more efficiently into the shadow region than the ambipolar field effect.

The cavity sidewalls itself also play an important role in guiding incoming ions to the innermost part of the cavity. Due to the oblique solar wind flow, the sunlit sidewall surface is charged a few tens of volts higher than the shadowed sidewall when compared at the same depth from the cavity entrance. The associated horizontal component of the electrostatic field acts to deflect ion trajectories slightly such that their collision with the sunlit sidewall is mitigated to some extent. The deflected ions can penetrate deeper and eventually contribute to the positive charging at the cavity bottom. The “ion-guiding” effect of a thin cavity is also an important aspect for the charging process proposed herein, because it implies that the ion-driven charging is likely to be developed for broader ranges of the solar irradiation angles than what is constrained by geometric configurations.

### 3.4. Effect of Photoelectron Emission

In the simulations presented thus far, we intentionally excluded the effects of photoelectron emission. In practice, the photoemission is recognized as a leading process for the surface charging in the sunlight (Grobman & Blank, 1969; Stubbs et al., 2014), as a typical photoemission current is in average greater than those of the solar wind as well as the Earth's magnetospheric plasmas. Inside the cavity, however, its role would differ from that commonly known for the charging of flat surfaces. This section discusses how the photoemission affects a current balance and the resultant charging properties. For this purpose, we examined two additional cases with photoemission for the solar irradiation angles  $\theta = 0^\circ$  and  $20^\circ$ . The major parameters of photoelectrons are as follows: the temperature is  $T_{pe} = 2.2$  eV and the current density is  $J_{pe} = 4.5 \mu\text{A}/\text{m}^2$  for normal solar incidence. Actual photoelectron yield at each sunlit location is scaled as  $\cos \theta$ , depending on the local solar incidence  $\theta$ . The cavity aspect ratio  $R_{D/W} = 4$  was used in the numerical experiments.

Figure 8 shows the potential profiles near the cavity. For  $\theta = 0^\circ$ , the plane and cavity bottom surfaces release photoelectrons, whereas the cavity sidewall does not. The surface potential outside the cavity is at a few volts



**Figure 8.** Two-dimensional potential profiles obtained from the simulations with photoelectron emission for (a)  $\theta = 0^\circ$  and (b)  $20^\circ$ .

positive and comparable to the photoelectron temperature, which is consistent with previous estimates of dayside surface potentials (Poppe & Horanyi, 2010). The photoelectron escaping current, which is restrained by the positive potential, is balanced with the solar wind electron inflow. In contrast, the potential structure inside the cavity remains similar to that obtained without photoemission. This result suggests that the function of electrons photoemitted in the depths of the cavity is limited. Owing to the reversed ordering of the solar wind current components  $(I_{i0} - I_{e0})|_{z=-z_b} > 0$ , negative excess charges need to be brought to the cavity bottom to establish a current balance there. The photoelectron release is, in principle, unable to take on this role because it tends to deposit positive charges to the surface and further lift up its positive potential. In fact, the cavity bottom potential is much greater than the photoelectron temperature and thereby virtually all photoelectrons emitted at the cavity bottom are recollected immediately. This implies that the photoelectrons emitted in situ have limited impact on the potential structure near the cavity bottom.

The role of photoelectrons in charging the inner surface of the cavity is manifested in a different manner. We demonstrate this in the simulation for  $\theta = 20^\circ$  (Figure 8b), in which (a part of) the sidewall surface in turn releases photoelectrons but the bottom does not. The left half of the cavity floor still maintains a rather high potential ( $> +600$  V), whereas the potential of the right half is relaxed to a few hundreds of volts. The partial relaxation of the positive potential at the cavity bottom is clearly caused by electrons photoemitted by the sidewall. The ion-driven cavity charging process generates an intense upward electric field inside the cavity. The electric field leads some of photoemitted electrons into the innermost part of the cavity. Such photoelectrons compensate for the build-up of excess positive charges at the cavity bottom due to ion bombardment.

The identified feature brings to light the important aspect of photoelectrons acting as negative charge carriers, which can move from a certain sunlit location to another (not necessarily sunlit) location on solid surfaces. This is clearly distinguished from the commonly quoted effect of photoelectrons for the charging in sunlight, that is, the process that transfers negative charges from the surface to space. The photoelectron ability to relax the differential charging is highly dependent on the surface topography of an area exposed to sunlight, as inferred from the comparison between the two different conditions for the solar irradiation angle. This also indicates the importance of the cavity geometry itself. Specifically, the proportion of a sunlit area in the sidewall seems to be one of crucial factors in the effect. Although the  $\phi_b$  dependence on  $R_{D/W}$  in the presence of photoemission is of special interest, this investigation should be handled carefully, taking into account its combination with sunlight conditions in the cavity. Further testing on practical cavity geometries will potentially elucidate this important aspect.

#### 4. Discussion

Although a cavity targeted in this study is limited to that with a specific geometry, the obtained results provide some clues to generalization of the revealed charging process. The significant positive charging directly reflects the directionality difference between electron and ion motions, which gets pronounced when the velocity ordering  $v_{te} > v_b > v_{ti}$  holds. Under the condition, electrons and ions would exhibit unbalanced penetrability against the cavity. This can lead to the strong differential charging between upper and deep areas of the cavity surface.

Similar charging processes have been recognized and investigated in the field of the plasma processing. During plasma etching of a typical dielectric structure such as a trench, the differential charging arises between upper and bottom parts of the structure (Arnold & Sawin, 1991; Hwang & Giapis, 1997; Ishchuk et al., 2012; Kinoshita et al., 1996; Memos & Kokkoris, 2016). The effect has been a subject of ongoing investigations (Memos & Kokkoris, 2016; Zhang, 2021) because the resulting electric field (or the potential difference of tens of volts) possibly causes some anomalies in the finish of the etching process. In this case also, differential features of electron and ion motions have been referred to as the root cause of the anomalous charging process. The present study demonstrates the analogy of physical processes emerging in these different application fields, in the light of electric charging of rough surfaces. We also note a difference between the two situations in that the kinetic energy of ions originates from the solar wind flow in the present study, while that is acceleration within the sheath in the plasma etching case. This distinction is directly related to the resultant magnitude of potentials developed in the two situations.

Here, we discuss a few important aspects that have not been addressed so far, although the detailed analysis on them is beyond the scope of the present study. One important aspect is the spatial scale of a cavity. The present numerical study considers a cavity of a few tens of meters on its long side, which can be encountered rarely in

nature. Thus a question that inevitably arises is how the charging condition will be for smaller cavities. One clue to this point is in the fundamental charging mechanism derived from the parametric study, which is described in Section 3.2. The physical root of the highly positive potential is electron depletion at the innermost part of a deep cavity, which is caused by shadowing of electrons by the sidewalls. This shadowing effect should be in principle governed by a dimensionless parameter, that is, the aspect ratio, rather than the size itself of the cavity. Furthermore, rather small, sub-Debye-scale cavities are considered to better fit this simple scaling law, as particle trajectories get less influenced by space charges inside the cavity. In view of the rough discussion, it is reasonable to assume that the ion-driven charging works also for small cavities.

The dependence of the charging properties on upstream plasma conditions is also a significant issue to consider. As far as the Moon and asteroids in the solar wind are concerned, the solar wind speed is obviously a key parameter, as the upper limit of a cavity bottom potential is constrained by ion drift kinetic energies. Although the present study employs a representative value of 400 km/s, the speed is subject to change depending on solar activity conditions. It is well known that the bulk velocity can approach 600–800 km/s in fast solar wind stream conditions. Such conditions would give rise to further significant charging exceeding a few kV positive at the bottom surfaces of deep cavities. The situation of the Moon inside the Earth's magnetosphere is also an interesting subject. For instance, the lunar surface will be exposed to hot ions of several keV in temperature during the Moon's traversals through the plasma sheet. We can speculate that the charging mechanism proposed in this study would not be as pronounced if the keV-energy ions were due to thermal motion. This is because incident hot ions have more divergent motion and are more likely to be lost at the side walls of the cavity. Of course, the above is a rather simplistic argument based on the findings of this study. In practice, the cavity potential will be determined in combination with other physical parameters such as the electron temperature as well as processes such as the charge relaxation by photoelectrons, both of which do play roles that cannot be ignored. Also, further complicating factors such as the presence of the lunar magnetic anomaly and other minor current sources (e.g., desorbed ion species) must be considered to foster a comprehensive understanding. The dependence on such upstream conditions need to be surveyed in the future works.

Possible contribution to mobilizations of small dust grains covering planetary bodies is another important aspect. The distinctive feature of the derived charging effect is that surface patches with positive charges are lying in the depths of the cavity and thereby their potential fields are hidden from upper space. Such localized potential difference may lead to an intense electrostatic field, which suggests possible implications for some sort of dust grain mobilizations. We should note that the present study does not conclude that the identified charging effect works exclusively on dust mobilizations in an electrostatic sense. It is reasonable to consider that the effect coexists with other charging modes such as proposed by Wang et al. (2016) inside the cavity, depending on a lighting condition of each surface patch. A critical implication from the series of studies is that solid surfaces with irregular geometries can produce irregular potential distributions even in sub-Debye scales. This also leads to the importance of investigating possible effects of the associated localized electric fields in the context of possible drivers of dust mobilizations. Since such investigations should suffer from an issue of numerous degrees of freedom regarding the structural features of cavities, not only deterministic simulations as addressed herein but also some statistical approaches would be necessitated.

## 5. Conclusions

The charging properties of a surface with a deep cavity are numerically studied with plasma conditions relevant to the solar wind. The investigations were conducted with applications to possible irregularities on the surface of solid planetary bodies in mind, although specific shape and size are employed in the simulations. The PIC computations predict the formation of positive potentials that reach a few to several hundreds of volts at the cavity bottom. In forming such unconventional charging state, incoming ions do play a lead role as positive charge carriers from space to the depths of the cavity. This is also supported by the parametric analysis indicating that the upper limit of the potentials is bounded by the kinetic energy of ions moving with a solar wind flow speed. Electron access to the cavity bottom is restricted to a considerable degree due to their much higher sticking rate to the sidewall compared with the ions. In this sense, the identified feature can be also regarded as one form of boundary-driven charging processes, in which the solid boundary exclusively shadows thermal electrons. The present study also identifies the creepage motions of photoelectrons as a major relaxation factor against the intense charging inside the cavity. The key finding is that photoelectrons emitted from the sidewall, not from the

bottom of the cavity, take this role. Based on this, the geometric configurations of the cavity itself and locations of the area irradiated by sunlight are inferred to be a crucial factor in determining the relaxation efficiency. To summarize, we have numerically demonstrated the unconventional fashion of surface charging in space, which may contribute to storage and release of electrostatic energies at the irregular surfaces of solid planetary bodies.

A critical issue at present is the lack of observational or experimental data that provide evidence of the physical process proposed herein. A significant feature of the present results is in the fact that the potential field itself is lying in the depths of the cavity structures and hidden from the upper space. Nevertheless, an intense electric field within the cavity potentially has an ability to accelerate positive charged particles upward. Thus remote observations of reflected ions or lofted dust grains coming from a surface with cavities and their correlations with environmental conditions may help providing evidence for the proposed scenario. Further numerical experiments should also be considered to develop generalized physical models of the charging process itself as well as its effects on charged particle transport. In particular, the scaling behavior of the charging process with respect to cavity size needs to be addressed to clarify its applicability to sub-Debye scale cavities.

## Data Availability Statement

The simulation data needed to reproduce the presented findings are available in the Zenodo open-access repository (Nakazono & Miyake, 2022).

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