



RESEARCH ARTICLE

10.1029/2021JA029654

Formation of the Thebe Extension in the Ring System of Jupiter

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Key Points:

- In Jupiter's warm and dense inner magnetosphere dust grains acquire high negative electric charges
- Dust particles ejected from Thebe with sufficient speeds contribute to the formation of the Thebe extension
- Instead of shadow resonances as suggested earlier an alternative mechanism is suggested for the formation of the Thebe extension

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Citation:

Borisov, N., & Krüger, H. (2021). Formation of the Thebe extension in the ring system of Jupiter. *Journal of Geophysical Research: Space Physics*, 126, e2021JA029654. <https://doi.org/10.1029/2021JA029654>

Received 11 JUN 2021

Accepted 9 OCT 2021

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Abstract Jupiter's tenuous dust ring system is embedded in the planet's inner magnetosphere, and—among other structures—contains a very tenuous protrusion called the Thebe extension. In an attempt to explain the existence of this swath of particles beyond Thebe's orbit, Hamilton and Krüger (2008), <https://doi.org/10.1038/nature06886> proposed that the dust particle motion is driven by a shadow resonance caused by variable dust charging on the day and night side of Jupiter. However, the model by Divine and Garrett (1983), <https://doi.org/10.1029/ja0888ia09p06889> together with recent observations by the Juno spacecraft indicates a warm and rather dense inner magnetosphere of Jupiter which implies that the mechanism of the shadow resonance does not work. Instead, we argue that dust grains ejected from Thebe due to micrometeoroid bombardment become the source of dust in the Thebe extension. We show that large (grain radii of a few micrometers up to multi-micrometers) charged dust grains having significant initial velocities oscillate in the Thebe extension. Smaller charged grains (with sub-micrometer radii) ejected from Thebe do not spend much time in the Thebe extension and migrate into the Thebe ring. At the same time, if such grains are ejected from larger dust grains in the Thebe extension due to fragmentation, they continue to oscillate within the Thebe extension for years. We argue that fragmentation of large dust grains in the Thebe extensions could be the main source of sub-micrometer grains detected in the Thebe extension.

1. Introduction

Jupiter has a highly structured dust ring system that extends along the planet's equatorial plane. It consists of the main ring, the halo, two gossamer rings, and the Thebe extension (Burns, 1984; Burns et al., 2004; Showalter et al., 1987). This dust system was investigated by the space missions Voyager 1,2, Galileo, Cassini, and New Horizons (Burns et al., 2004; Ockert-Bell et al., 1999; Owen et al., 1979; Porco et al., 2003; Showalter et al., 2007; Smith et al., 1979; Throop et al., 2016) and also by telescopes in space (Hubble) and from the Earth (Keck; de Pater et al., 1999, 2008; Showalter et al., 2008).

Usually it is assumed that the gossamer rings are formed by dust grains ejected from the surfaces of the corresponding moons (Thebe and Amalthea) due to micrometeorite bombardment (Dikarev et al., 2006; Krivov et al., 2002, 2003). Recently it has been argued that a supplementary mechanism of dust grain ejection from the polar regions of Thebe and Amalthea, that is, electrostatic lofting, contributes to the formation of the gossamer rings (Borisov & Krüger, 2020). At the same time, the mechanism of the formation of the Thebe extension is not so clear. Indeed, it is known that Jupiter's corotational radial electric field acts on dust grains in the planet's inner magnetosphere (Horányi & Burns, 1991). The corresponding electric force for negatively charged grains in the gossamer rings is directed inwards (toward Jupiter) for radial distances $r > R_{\text{synch}}$, where $R_{\text{synch}} = 2.27 R_J$ is the radius of the synchronous orbit, that is, the orbit at which the angular frequency of a body orbiting Jupiter is equal to the angular frequency of Jupiter's rotation ($R_J = 71492$ km is the radius of Jupiter). On the contrary, positively charged grains are pulled outwards by this electric field (into the Thebe extension).

The sign and the magnitude of the electric charge on a dust grain in Jupiter's shadow are determined only by the plasma parameters in the inner magnetosphere of Jupiter, and additionally on the sun-lit side by the action of the solar UV radiation. Unfortunately, real plasma parameters of Jupiter's inner magnetosphere are still not well-known. Earlier in the theoretical investigations devoted to dust grains dynamics in the gossamer rings the authors often estimated the electron concentration in the inner magnetosphere of Jupiter as of the order of $N_e \sim 1 \text{ cm}^{-3}$ or even less, and the electron temperature of a few electron volts, see, for

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example, Hamilton and Krüger (2008) and Horányi and Burns (1991). In such a plasma environment, the electric potential on dust grains on the sun-lit side can be positive, thus driving such charged dust grains outwards. This mechanism was suggested by Hamilton and Krüger (2008) to explain the formation of the Thebe extension. At the same time, according to the well-known theoretical model of thermal plasma in the inner magnetosphere of Jupiter by Divine and Garrett (1983), the electron concentration in the vicinity of Thebe is predicted to be $N_e \approx 50 \text{ cm}^{-3}$ and the electron temperature $T_e \approx 45 \text{ eV}$. This model is based on Pioneer and Voyager data and was confirmed later by Garrett et al. (2005) (only slightly corrected). For such large values of the electron concentration and temperature, the electric charges on dust grains are definitely negative and rather high, both on the sun-lit side and in the planet's shadow. Furthermore, for such large concentrations of thermal electrons the variation of the electric potential on the sun-lit side and in the shadow of Jupiter should be almost negligible (as an example how the electric potential changes with the growth of the plasma concentration see Horányi & Burns, 1991, their Figure 5). As a result, assuming that the Divine model is correct, the above-mentioned explanation of the Thebe extension does not work, and a new physical mechanism for its formation has to be developed.

In relation with the model by Divine and Garrett (1983) two aspects should be emphasized. First, new experimental data obtained by the Juno mission at $R \approx 10 R_J$ clearly demonstrate that the concentration of ions grows rather quickly toward smaller distances from Jupiter (Kim et al., 2020). Second, it is expected that later on (at the end of its mission) Juno will provide us with the real concentrations of charged particles at $R \approx 3 R_J$.

According to the experimental data, the Thebe extension is a very faint structure (dust concentration is smaller than in the gossamer rings, see Burns et al., 1999; Krüger et al., 2009; Ockert-Bell et al., 1999). This means that possibly not all dust grains ejected from Thebe penetrate into the Thebe extension but only some fraction. The radial range of the Thebe extension as seen in images (Ockert-Bell et al., 1999) comprises at least approximately $0.64 R_J$ (from the orbit of Thebe at $3.11 R_J$ out to $3.75 R_J$) which is in agreement with in situ dust measurements by the Galileo spacecraft (Krüger et al., 2009).

In this article, we take into account that dust grains lofted from the moons' surface can have rather high initial velocities. Velocities of the ejected dust grains and their directions of propagation were investigated by various authors, for example, Eichhorn (1978), Gault et al. (1963), Koschny and Grün (2001), O'Keefe and Ahrens (1985), and Sachse et al. (2015), and a recent review by Szalay et al. (2018). Laboratory measurements together with numerical simulations were applied to obtain the distributions of masses, velocities, and their directions as functions of a meteorite (micrometeorite) parameters. Various authors obtained quite different maximum ejection speeds, ranging from approximately $700 - 800 \text{ m s}^{-1}$ up to 20 km s^{-1} .

In addition to these so far inconclusive results based on laboratory measurements, another line of evidence comes from in situ dust measurements in the Jovian system: Impact ejecta dust clouds were directly measured at the Galilean moons (Krüger et al., 1999, 2003). These tenuous clouds were detected in the vicinity of these moons up to an altitude of approximately eight satellite radii. It implies that the particles must have been ejected from the surfaces of these moons with speeds not too far below their escape speeds, which are in the range of approximately 2.5 km s^{-1} . Furthermore, the Galileo detector measured a very tenuous dust ring around the planet in the region between the Galilean moons. These particles were interpreted (at least partially) as being ejecta from these moons (Krivov et al., 2002). Therefore, they must have reached ejection speeds even exceeding the escape speeds of the Galilean moons. Given that the surface properties of Amalthea and Thebe are likely comparable (dirty ice), we assume similar ejection speeds also for these small moons.

In our calculations, we shall use some intermediate values of dust grains ejected velocities (a few km s^{-1}) which are in the range of the escape speeds from the Galilean moons. Previously, while discussing dust dynamics in the gossamer rings and Thebe extension, the role of a dust grain initial velocity was neglected. Taking into account the initial velocity makes it possible to explain the penetration of some fraction of dust grains ejected from Thebe into the Thebe extension. There are some peculiarities of the discussed process. The ejected grain should have a significant initial velocity with the appropriate direction of propagation. The most favorable situation appears when a given large dust grain is ejected from the surface of Thebe in the direction of Thebe's instant azimuthal velocity or, more generally, the grain at the moment of ejection has a significant velocity component in the direction of the instantaneous azimuthal speed of Thebe and the

radial velocity directed into the Thebe extension. The discussed requirements are easily realized if Thebe and a micrometeorite hitting the surface move toward each other with antiparallel speed vectors. Note that in such case the relative velocity of two bodies can exceed 50 km s^{-1} .

According to our calculations dust grains with sizes of the order of several micrometers ejected with velocities $V_\theta \geq 1.5 \text{ km s}^{-1}$ penetrate deep into the Thebe extension. At the same time, smaller grains (fraction of a micrometer) penetrate into the Thebe extension only at the initial stage after ejection from Thebe. Later on, their radial localization shifts more and more into the Thebe ring. That is why tiny grains appear in the Thebe extension mainly due to some other mechanism. According to Burns et al. (2004) tiny dust grains are produced in Jupiter's rings due to "sputtering of surrounding plasma and collisions with gravitationally focused interplanetary micrometeorites". Later on Dikarev et al. (2006)—based on these ideas—developed the model of two-stage dust delivery from satellites to planetary rings. According to this model large (multi-micrometer-sized) dust grains ejected from the surfaces of the moons supply the rings with tiny dust grains due to collisions between themselves and with other micrometeorites. Note that the influence of electric charging on the dust grains dynamics was neglected in this model.

In this article, we argue that some parts of large (from a few micrometers up to multi-micrometer sizes) electrically charged grains ejected from Thebe due to collisions with micrometeorites penetrate deep into the Thebe extension. Smaller dust grains appear subsequently due to fragmentation of large grains in the Thebe extension (caused by sputtering, mutual collisions, and collisions with micrometeorites or by electric disruption). Note that small electrically charged dust grains ejected from Thebe migrate rather quickly into the Thebe ring. At the same time, we show that similar grains that appear in the Thebe extension due to fragmentation of large grains remain in the extension for years.

2. Basic Equations

In order to discuss the motion of dust grains in the equatorial inner magnetosphere of Jupiter, we use a cylindrical coordinate system centered at Jupiter. Suppose that the z -axis is directed upwards while the magnetic field lines of Jupiter are directed downwards. Two other coordinates are the radial coordinate in the equatorial plane r and the angular coordinate θ . The equations of motion for charged dust grains in this coordinate system were investigated earlier by Horányi and Burns (1991). We present them in the following form:

$$\begin{aligned} \frac{d^2 r}{dt^2} &= r\Omega^2 + \frac{q}{r^2}(\Omega - \Omega_J) - \frac{\mu}{r^2} \\ \frac{d\Omega}{dt} &= -\frac{d \ln r}{dt} \left(\frac{q}{r^3} + 2\Omega \right). \end{aligned} \quad (1)$$

Here $\Omega = d\theta/dt$ is the angular frequency of the orbiting dust grain, $\Omega_J \approx 0.000176 \text{ s}^{-1}$ is the angular frequency of Jupiter's rotation, $q = Z\Omega_{He}R_{Th}^3 m_e / M_d$, Ω_{He} is the Larmour frequency of electrons on the surface of Jupiter, $\Omega_{He} \approx 8.5 \cdot 10^7 \text{ s}^{-1}$, m_e , M_d are the masses of an electron and a dust grain, respectively, $Z = Q_d/e$ is the amount of elementary charges on a given dust grain, e is the charge of the electron, Q_d is the charge on a dust grain, $\mu = GM_J$, $G = 6.68 \cdot 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2}$ is the gravitational constant, $M_J \approx 1.9 \cdot 10^{30} \text{ g}$ is the mass of Jupiter, and $R_{Th} = 3.11 R_J$ is the radial distance of Thebe's orbit from Jupiter.

Equation 1 describes the motion in the equatorial plane of Jupiter of a grain with the electric charge Q_d and mass M_d . The magnetic field has a dipole form. It is assumed that the inner magnetosphere rigidly corotates with the planet. Two forces—the gravitational force (term μ/r^2) and the electric force (term $q(\Omega - \Omega_J)/r^2$)—determine the motion of a dust grain. Previously, the dynamics of a charged grain ejected with zero initial velocity with respect to the moon was considered (see, e.g., Horányi & Burns, 1991). Here, we discuss the more general and more realistic case that ejected grains have initial radial and azimuthal velocities (Sections 3 and 5). This is quite natural because dust grains are ejected from the moon due to micro-explosions caused by micrometeorite bombardment. It is important that some ejected grains have higher initial azimuthal velocities than the azimuthal velocity of the moon. We show that such large dust grains (with small ratio Q_d/M_d) have equilibrium orbits shifted outwards with respect to the orbit of the moon (see Figures 1 and 3).

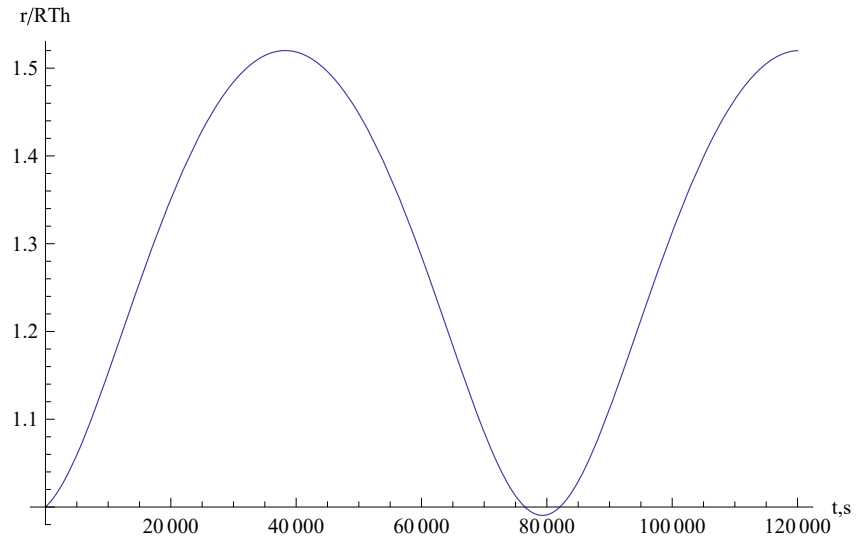


Figure 1. Radial motion of a dust grain without electric charge. The horizontal axis gives the time in seconds and the vertical axis the relative radial coordinate r/R_{Th} . The initial radial velocity directed into the Thebe extension is $V_r(t=0) = 1.5 \text{ km s}^{-1}$. The initial azimuthal velocity with respect to the azimuthal velocity of Thebe is $V_\theta = 2.2 \text{ km s}^{-1}$. The grain starts its motion at $t = 0$ from the orbit of Thebe.

Note that the electric charge on a dust grain Q_d is not constant. Usually, dust grains lying on the surface of the moon (Thebe in our case) have electric charges much smaller than the electric charges in equilibrium in space (Borisov & Mall, 2006). That is why after ejection from the surface dust grains continue to acquire electric charge approaching an equilibrium value Q_{st} .

Let us proceed with the second of Equation 1. It is convenient to seek for $\Omega(t)$ in the form:

$$\Omega(t) = \Omega_1(t) \frac{R_{Th}^2}{r^2}. \quad (2)$$

The equation for Ω_1 takes the form:

$$\frac{d\Omega_1}{dt} = -\frac{q(t)}{R_{Th}^2} \frac{dr}{dt}. \quad (3)$$

This equation can also be written in the equivalent form which is more convenient for an approximate solution in case of a changing charge $q(t)$:

$$\frac{d\Omega_1}{dt} = \frac{1}{R_{Th}^2} \frac{d}{dt} \left(\frac{q}{r} \right) - \frac{1}{r R_{Th}^2} \frac{dq}{dt}. \quad (4)$$

If a dust grain starts its motion from the surface of Thebe with negligible velocity, the initial condition for Ω_1 is $\Omega_1(0) = \Omega_{Th}$, where $\Omega_{Th} \approx 0.000107 \text{ s}^{-1}$ is the angular orbital rotation frequency of Thebe. If the initial azimuthal velocity V_θ in the system moving with Thebe is finite $\Omega_1(0) = \Omega_{Th} + \Delta\Omega$, where $\Delta\Omega = V_\theta/R_{Th}$. As a result the frequency Ω takes the form:

$$\Omega(t) = (\Omega_{Th} + \Delta\Omega) \frac{R_{Th}^2}{r^2} + \frac{1}{r^2} \left[\frac{q(t)}{r} \right]_0^t - \frac{1}{r^2} \int_0^t \frac{1}{r} \frac{dq}{dt} dt. \quad (5)$$

Here $q(0) = Z_0 \Omega_{He} R_{Th}^3 m_e / M_d$, Z_0 is the amount of electrons on a given dust grain lying on the surface of the moon $Z_0 = Q_0/e$, $r_0 = R_{Th}$ is the initial radial coordinate.

If the electric charge is constant, $q = q_{st}$, the derivative is $dq/dt = 0$. In this case, we find:

$$\Omega(t) = \Omega_0 \frac{R_{Th}^2}{r^2} + \frac{q_{st}}{r^2} \left(\frac{1}{r} - \frac{1}{R_{Th}} \right), \quad (6)$$

where Ω_0 is the initial angular frequency. If the radial coordinate of a given dust grain $r(t)$ changes more significantly than the electric charge $q(t)$ ($\left| \frac{dr}{r dt} \right| \gg \left| \frac{dq}{q dt} \right|$) then we receive an approximate solution which is more general than the result given in Equation 6:

$$\Omega(t) = \Omega_0 \frac{R_{\text{Th}}^2}{r^2} + \frac{q(t)}{r^2} \left(\frac{1}{r} - \frac{1}{R_{\text{Th}}} \right). \quad (7)$$

Here $\Omega_0 = \Omega_{\text{Th}} + \Delta\Omega$. With increasing time $q(t) \rightarrow q_{\text{st}}$, where q_{st} is the equilibrium charge on a dust grain in space. It follows from Equations 5 and 7 that for the moment $t = 0$ the frequency $\Omega = \Omega_{\text{Th}} + \Delta\Omega$, as it should be. Note that the sign of q is positive for negatively charged grains because the magnetic field of Jupiter is directed downwards.

It is easy to check that the expression for $\Omega(t)$ given by Equation 5 is the solution of the second of Equation 1. As a result, we may conclude the following. First, the last term on the right-hand side of Equation 7 is positive for radial distances r less than the orbit of Thebe R_{Th} . Second, the smaller the variations $|R_{\text{Th}} - r|$, the less significant is the influence of the electric charge on the angular frequency. For a rather large time $t \geq t_{\text{st}}$ when $Q(t) = Q_{\text{st}}$ we may designate $\Omega_0 R_{\text{Th}}^2 - q_{\text{st}}/R_{\text{Th}} = J$ and express the angular frequency as:

$$\Omega(t) = \frac{J}{r^2} + \frac{q_{\text{st}}}{r^3}. \quad (8)$$

It can be shown that our Equation 8 coincides with Equation 3b of Horányi and Burns (1991). But for a smaller period of time $t \leq t_{\text{st}}$, we may use a more general expression:

$$\Omega(t) = \frac{J}{r^2} + \frac{q(t)}{r^3} - \frac{q(t) - q_{\text{st}}}{r^2 R_{\text{Th}}}. \quad (9)$$

The frequency $\Omega(t)$ given by Equation 9 can be substituted into the first Equation 1 to obtain an equation describing the radial motion of a dust grain. Assuming as in the article by Horányi and Burns (1991) that the terms with the electric charge are small and retaining only the terms of the first order with respect to q , we arrive at an approximate equation:

$$\frac{d^2 r}{dt^2} = \frac{J^2}{r^3} + \frac{3qJ}{r^4} - \frac{2(q - q_{\text{st}})J}{r^3 R_{\text{Th}}} - \frac{\mu + q\Omega J}{r^2}. \quad (10)$$

3. Neutral Dust Grain Dynamics

Let us introduce the dimensionless coordinate $\rho = r/R_{\text{Th}}$ instead of the radial distance r . If the electric charge is negligible ($q(t) \rightarrow 0$), Equation 10 describes the radial motion of a neutral dust grain:

$$\frac{d^2 \rho}{dt^2} = \frac{J^2}{R_{\text{Th}}^4 \rho^3} - \frac{\mu}{R_{\text{Th}}^3 \rho^2}. \quad (11)$$

It can be shown with the help of Equation 11 that at the moment $t = 0$ when $\rho = 1$ the radial force is positive if $\Delta\Omega > 0$. With increasing ρ this force decreases and at $\rho = \rho_*$, where $\rho_* = J^2(R_{\text{Th}}\mu)^{-1}$ it becomes equal to zero. For larger distances $\rho > \rho_*$, this force is negative and it pulls dust grains radially inwards into the Thebe ring.

Let us discuss the radial motion of a neutral dust grain analytically. It follows from Equation 11:

$$\left(\frac{d\rho}{dt} \right)^2 = \frac{2\mu}{R_{\text{Th}}^3 \rho} - \frac{\Omega_0^2}{\rho^2} + W_0, \quad (12)$$

where W_0 is added on the right-hand side of Equation 12 to include the correct value of the initial radial velocity V_r :

$$W_0 = \Omega_0^2 - \frac{2\mu}{R_{\text{Th}}^3} + \frac{V_r^2}{R_{\text{Th}}^2}. \quad (13)$$

From Equation 13, we find the maximal radial excursion ρ_{max} for a given dust grain:

$$\rho_{\text{max}} = -\frac{\mu}{R_{\text{Th}}^3 W_0} + \sqrt{\left(\frac{\mu}{R_{\text{Th}}^3 W_0} \right)^2 + \frac{\Omega_0^2}{W_0}}. \quad (14)$$

In Figure 1, we show the radial distance of a dust grain for an initial azimuthal $V_\theta = 2.2 \text{ km s}^{-1}$ and radial $V_r = 1.5 \text{ km s}^{-1}$ velocities. The initial azimuthal velocity is taken in the direction of Thebe's orbital motion, and the radial velocity is directed toward the Thebe extension. It can be seen that neutral dust grains with such significant initial velocities propagate rather far outside of the Thebe orbit regardless of their size. In

our case, the grain propagates up to $\rho_{\max} = 1.52$, which is equivalent to approximately 115,000 km. According to Figure 1, it takes a significant amount of time $\Delta t \approx 22$ hours for a neutral dust grain to penetrate into the Thebe extension and to return to its initial radius $\rho = 1$. The maximum radial velocity reaches the value $V_{\max} \approx 6 \text{ km s}^{-1}$. Note that such dynamics is valid for all neutral dust grains (with given initial velocities) regardless of their mass. The situation changes if we take into account that dust grains are negatively charged and the ratio of the electric charge to mass Q_d/M_d varies significantly for grains with different sizes a . Indeed, under equilibrium conditions the electric charge on a given dust grain with radius a is $Q_d = \phi_{\text{st}} a$, while the mass of such grain is $M_d = (4\pi/3)\rho_{\text{dust}} a^3$, where ϕ_{st} is the electric potential in the medium, ρ_{dust} is the dust density. The ratio Q_d/M_d is inversely proportional to a^2 . Thus, the electric force influences more significantly the motion of small dust grains. That is why the motion of neutral dust grains discussed in this section can be considered as a good approximation for the dynamics of large multi-micrometer sized dust grains. We will discuss the influence of the electric charge and mass on the dust grains dynamics in more detail in the next sections.

4. Charging of a Dust Grain on the Surface of the Moon and in Space

In this section, we discuss charging of dust grains in the inner magnetosphere of Jupiter taking into account the Divine model (Divine & Garrett, 1983). At the beginning, we estimate the initial electric charge on a grain lying on the surface of the moon (Thebe). Then we consider the equilibrium charge on the same grain ejected from the surface. At the end, we investigate how the electric charge on a given grain grows in time after ejection from the moon.

The problem of dust grains charging was discussed in many articles, see, for example, Borisov and Mall (2006), Goertz (1989), Havnes et al. (1987), Horányi (1996), Whipple (1981), and Whipple et al. (1985). We present some estimates for the typical electric charge on a dust grain with radius a lying on the surface of the moon and also in space after ejection.

The process of dust grain charging is considered in the system of coordinates rotating with the magnetic field. This means that there is no corotating electric field acting on electrons and ions but instead there exists an azimuthal velocity component of a dust grain with respect to the plasma $V_0 = R_d(\Omega_d - \Omega_J)$, where R_d is the radial distance of a dust grain from Jupiter, Ω_d is its angular velocity, Ω_J is the angular velocity of the planet (and the magnetic field). In general, this velocity should be taken into account when discussing dust grain charging by ions. Below it is shown that in our case the additional flux of ions associated with this velocity is smaller than the well-known flux of ions in the vicinity of a grain (see, e.g., Goertz, 1989; Havnes et al., 1987; Horányi, 1996; Whipple, 1981; Whipple et al., 1985) that provides its charging. Hence, to a first approximation the velocity V_0 can be neglected.

In order to calculate the equilibrium potential, we assume that far away from the moon electrons have a Boltzmann distribution with the temperature T_e and concentration N_e :

$$F_e = \frac{N_e}{\pi^{3/2} V_{T_e}^3} \exp\left(-\frac{v^2}{V_{T_e}^2}\right), \quad (15)$$

where $V_{T_e} = \sqrt{2T_e/m_e}$ is the thermal velocity, and m_e is the mass of an electron. Ions are assumed to have a similar distribution:

$$F_i = \frac{N_i}{\pi^{3/2} V_{T_i}^3} \exp\left(-\frac{v^2}{V_{T_i}^2}\right), \quad (16)$$

where $N_i = N_e = N_0$ is the plasma concentration, T_i is the temperature and $V_{T_i} = \sqrt{2T_i/M_i}$ is the thermal velocity of ions, M_i is the mass of ions.

Our aim is to estimate the electric potential ϕ on the surface of the moon in a plasma that contains electrons and ions with the distribution functions (Equations 15 and 16) far away from the surface. This potential should be negative because the thermal speed of electrons is much higher than the thermal speed of ions $V_{T_e} \gg V_{T_i}$. Let us introduce the Debye radius $R_D = V_{T_e}/\Omega_{pe}$. Here $\Omega_{pe} = (4\pi e^2 N_e/m_e)^{1/2}$ is the plasma frequency, e is the charge of an electron. The Debye radius in the vicinity of Thebe according to the Divine model is of the order of $R_d \approx 1 - 2$ m.

Electrons are retarded by the negative potential. Their concentration in the plasma with the potential ϕ is $N_e = N_0 \exp(e\phi/T_e)$ while the velocity distribution is still determined by Equation 15. The flux of electrons on to the negatively charged surface according to Havnes et al. (1987) is:

$$\Phi_e = \sqrt{\frac{2}{\pi}} V_{Te} N_0 \exp\left(\frac{e\phi}{T_e}\right). \quad (17)$$

At the same time, the flux of ions onto the same surface is:

$$\Phi_i = \sqrt{\frac{2}{\pi}} V_{Ti} N_0 \left(1 - \frac{e\phi}{T_i}\right). \quad (18)$$

Equating the fluxes of electrons and ions we find for the electric potential under equilibrium conditions and equal temperatures $T_e = T_i$:

$$(1 + F_{st}(a)) \exp(F_{st}(a)) = \frac{V_{Te}}{V_{Ti}}, \quad (19)$$

where $F_{st} = -e\phi_{st}/T_e$. For equal temperatures of electrons and ions and heavy ions ($M_i/m_e \approx 3 \cdot 10^4$), the electric potential on the surface is $e\phi_s/T_e \approx -3.6$. The electric field above the surface of the moon is described by the Poisson equation:

$$\frac{d^2\phi}{dz^2} = 4\pi e(N_e(\phi) - N_i(\phi)), \quad (20)$$

where z is the coordinate across the surface of the moon. A detailed calculation of the surface electric field can be found in Borisov and Mall (2006). According to this article, the characteristic length that determines the electric field is $L_z \approx (3 - 4)R_D$. So we estimate the vertical surface electric field as $E_s \approx (0.3 \div 0.4) \text{ V cm}^{-1}$. This field is connected with the density σ of the electric charge on the surface that provides such electric field E_s , see Borisov and Mall (2006). Indeed, after integration of Equation 20 across the surface we arrive at the relation:

$$\frac{d\phi}{dz}\Big|_{+0} - \frac{d\phi}{dz}\Big|_{-0} = 4\pi\sigma. \quad (21)$$

This equation allows us to estimate the charge on a dust grain with the radius a lying on the flat surface. Taking into account that the cross-section of a dust grain is $\Sigma = \pi a^2$, we find the electric charge on a grain lying on the surface as $Q_d = 0.5a^2 E_s$. For example, the grain with the radius $a = 5 \mu\text{m}$ lying on the surface of the moon (Thebe) contains 5 to 6 electrons ($Z = 5 - 6$).

After ejection from the moon, a dust grain acquires additional negative electric charges until its potential ϕ_{st} reaches an equilibrium value (which is achieved when the flux of electrons hitting a given grain becomes equal to the flux of ions). It is more convenient to use the dimensionless parameter $F = -e\phi/T_e$ instead of the potential ϕ .

It is interesting that the electric potential determined above by Equation 19 in the vicinity of a grain can accelerate ions up to the velocity $V_b \approx (-2e\phi_{st}/M_i)^{1/2}$ toward a grain. This velocity comprises $V_b \approx 35 \text{ km s}^{-1}$ and it is higher than the thermal speed of ions ($V_b \approx 1.9 V_{Ti}$). At the same time, the azimuthal velocity of a dust grain with respect to the magnetic field (mentioned at the beginning of this section) in the vicinity of Thebe is $V_0 \leq 15 \text{ km s}^{-1}$. As a result, the flux of ions given by Equation 18 is significantly larger than the flux Φ_0 associated with the azimuthal velocity V_0 , which provides additional charging mainly from one side $\Phi_0 \approx \pi a^2 N_0 V_0$.

Note that while calculating the electric potential we have not included the flux of secondary electrons. This flux contains several parameters whose values are rather uncertain. For the same values of parameters that were used earlier in relation with the inner magnetosphere of Jupiter (Horányi & Burns, 1991), we find that the deviation of the surface potential from the one estimated above is only approximately 1.5%. Taking into account that the electric potential ϕ_{st} is connected with the equilibrium electric charge on a given dust grain by the relation $\phi_{st} = Q_d/a$, we are able to estimate the equilibrium electric charge on a dust grain with radius a in space. This calculation shows that in the vicinity of Thebe a dust grain with radius a should have the charge $Q_d \approx 3.6 a T_e/e$ under equilibrium conditions. For a grain with radius $a = 5 \mu\text{m}$, the charge is $Q_d \approx 5 \cdot 10^5 e$ ($Z = 5 \cdot 10^5$). It should be mentioned that the electric charge on a grain lying on the surface is proportional to the square of its radius while in space the equilibrium charge is proportional only to its

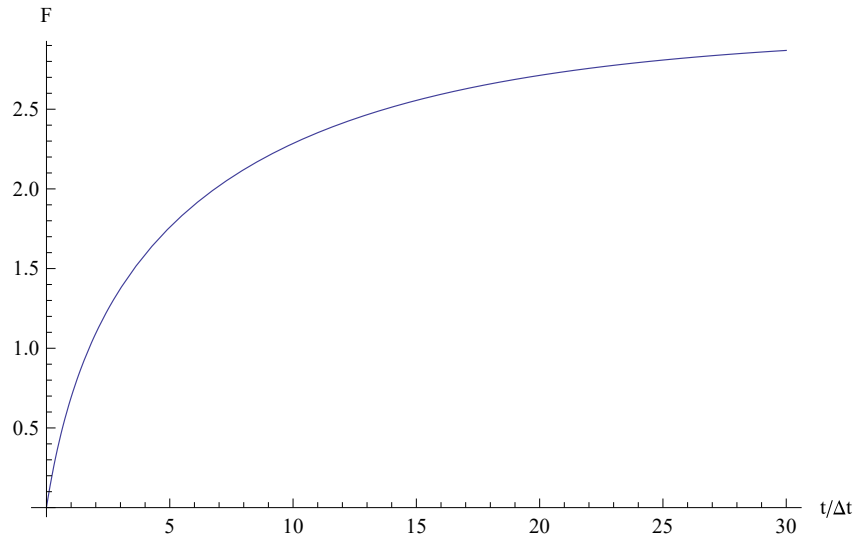


Figure 2. Growth of the electric potential toward its equilibrium value in time on a given dust grain with the radius $a = 1 \mu\text{m}$ after its ejection from Thebe at $t = 0$. On the horizontal axis time in dimensionless units $t/\Delta t$ is presented.

radius. Nevertheless, for $a = 5 \mu\text{m}$ the charge in space is approximately five orders of magnitude higher than the charge on the same grain lying on the surface.

Now we need to investigate how the electric charge on a given dust grain changes in time. For this purpose, we take into account the difference of the fluxes of electrons and ions that provide the growth of the electric charge:

$$\frac{dQ_d}{dt} = 4\pi a^2 e(\Phi_i(a) - \Phi_e(a)). \quad (22)$$

This equation rewritten in terms of the dimensionless function F takes the form:

$$\frac{dF(a)}{dt} = \frac{\sqrt{2\pi}V_{Te}a}{R_d^2} \left(\exp(-F(a)) - \frac{V_{Ti}}{V_{Te}}(1 + F(a)) \right). \quad (23)$$

The dimensionless potential $F(a)$ grows in time approaching its equilibrium value $F_{st}(a) \approx 3.6$. With the help of Equation 23, it is possible to estimate the characteristic period Δt of charging:

$$\Delta t \approx \frac{R_d^2}{\sqrt{2\pi}V_{Te}a}. \quad (24)$$

It follows from Equation 24 that the period Δt is inversely proportional to the radius of a grain. For a dust grain with radius $a = 1 \mu\text{m}$, this time is of the order of one second. Note that Δt describes the characteristic period for the initial stage of charging. More accurately, the variation of the potential $F(a)$ can be obtained solving Equation 24 numerically. In Figure 2, we show the growth in time of the potential $F(a)$ for the grain size $a = 1 \mu\text{m}$. On the horizontal axis the dimensionless time $t_1 = t/\Delta t$ is given. It is seen that the process of charging becomes slower and slower with time. It takes the time $15\Delta t$ to achieve $0.7F_{st}(a)$.

5. Dust Grain Dynamics in the Thebe Extension

The dust grain dynamics after ejection from the moon with some finite initial velocity can be investigated numerically. The radial displacement in time of the charged dust grains with different sizes $a = 5 \mu\text{m}$ and $a = 0.3 \mu\text{m}$ are calculated taking into account the equations of motion (see Section 2). The results are shown in Figures 3 and 4. The initial azimuthal and radial velocities are $V_\theta = 2.2 \text{ km s}^{-1}$ and $V_r = 1.5 \text{ km s}^{-1}$ (the same for both grains). The calculations are carried out based on the Divine model. It is seen that the heavy charged dust grain penetrates rather deep into the Thebe extension (approximately 100,000 km). This result qualitatively corresponds to the motion of a neutral dust grain (see Figure 1). Only the radial excursion into the Thebe extension is somewhat smaller due to the action of the electric force. At the same time, the

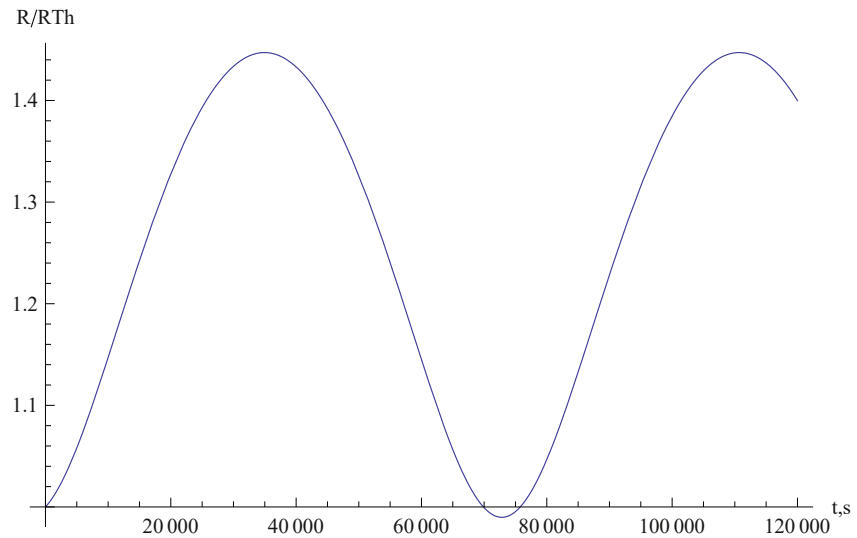


Figure 3. Radial oscillations in time of a charged dust grain with the radius $a = 5 \mu\text{m}$ ejected from Thebe. The horizontal axis shows the time in seconds and the vertical axis the radial coordinate in dimensionless units r/R_{Th} . The initial radial velocity directed outwards is $V_r = 1.5 \text{ km s}^{-1}$ and the azimuthal velocity with respect to the azimuthal velocity of Thebe is $V_\theta = 2.2 \text{ km s}^{-1}$.

submicrometer dust grain at the beginning slightly penetrates into the Thebe extension and later on its radial motion shifts into the Thebe ring. It is interesting to mention that the period of radial oscillations for a smaller dust grain is much shorter than that for the larger one. Such an effect was not discussed before. It happens because strong electric charging of a dust grain (that exists due to high plasma concentration and temperature) influences the period of oscillations.

All calculations above were carried out assuming that dust grains (small and large) were ejected from the surface of Thebe. Now we suppose that a small dust grain appears in the Thebe extension due to fragmentation of a larger dust grain (e.g., in collision with a micrometeoroid). In Figure 5, we present one such example. A dust grain with the size $a = 0.3 \mu\text{m}$ is released at $t = 0$ from a large grain in the vicinity of $r = 1.22R_{\text{Th}}$. It is assumed that the small grain is ejected with the radial velocity $V_r(t = 0) = 2.8 \text{ km s}^{-1}$ and the angular frequency $\Omega(t = 0) = 0.000078 \text{ s}^{-1}$.

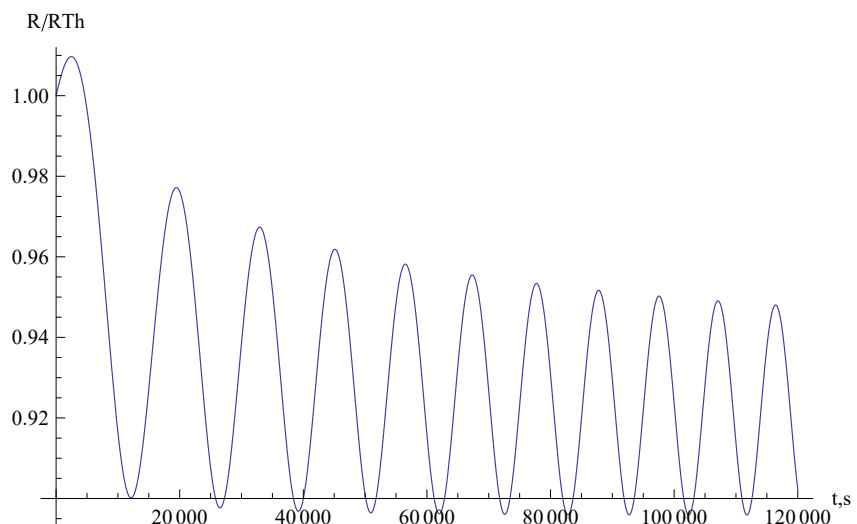


Figure 4. The same as in Figure 3, except that the radius of a dust grain is $a = 0.3 \mu\text{m}$.

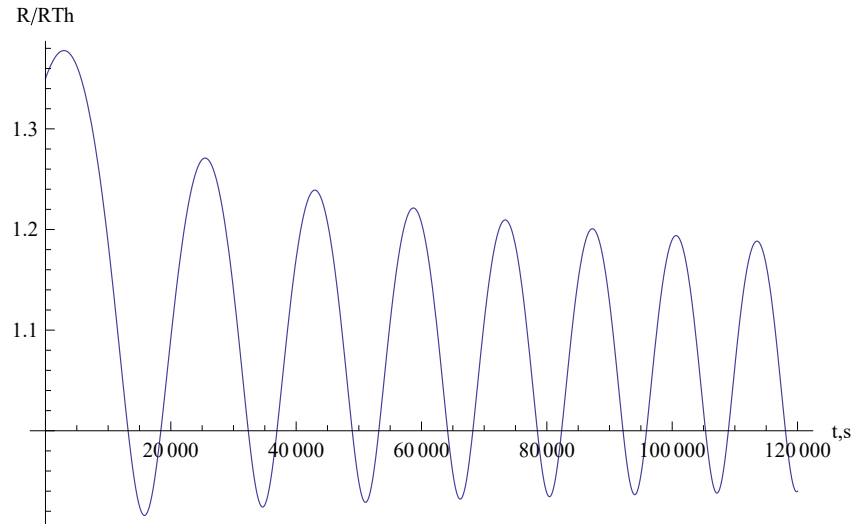


Figure 5. Radial oscillations of a small dust grain ($a = 0.3 \mu\text{m}$) ejected at $r_0 = 1.22 R_{\text{Th}}$ with the initial radial velocity equal to the corresponding velocity of a large dust grain $V_r(t = 0) = 2.8 \text{ km s}^{-1}$. The initial azimuthal frequency $\Omega(t = 0) = 0.000078 \text{ s}^{-1}$ coincides with the angular frequency of a large dust grain located at $r_0 = 1.22 R_{\text{Th}}$.

In contrast to the results presented in Figure 4, this small dust grain does not migrate into the Thebe ring but continues to oscillate in the Thebe extension. In the equilibrium state, the oscillations take place between $r_1 \approx 0.96 R_{\text{Th}}$ and $r_2 \leq 1.22 R_{\text{Th}}$. This is a new result because earlier it was found that the stationary orbit of dust grains should be shifted inwards from the moon due to the action of the electric field, see, for example, Horányi and Burns (1991). Such distinction appears because of the different initial conditions.

To better understand the situation, we have calculated the potential describing the radial motion of a small dust grain with a constant electric charge:

$$\frac{1}{2} \left(\frac{d\xi}{dt} \right)^2 = U(\xi) + W_0. \quad (25)$$

Here $U(\xi)$ is the potential:

$$U(\xi) = -\frac{\Omega_0^2 \xi^4}{2\xi^2} - \frac{\Omega_0 q}{R_{\text{Th}}^3 \xi^2} \left(\frac{1}{\xi} - \frac{1}{\xi_0} \right) - \frac{q^2}{2R_{\text{Th}}^6 \xi^2} \left(\frac{1}{\xi} - \frac{1}{\xi_0} \right)^2 + \frac{\mu + q\Omega_J}{R_{\text{Th}}^3 \xi}, \quad (26)$$

where $\xi = r/R_{\text{Th}}$, Ω_0 is the initial angular frequency $\Omega_0 = \Omega(t = 0)$, ξ_0 is the initial radial position of a given dust grain, W_0 is a constant added in Equation 25 to provide the correct initial velocity.

In Figure 6, we present the potential $U_1(\xi) = U(\xi) + W_0$ for a dust grain starting from $\xi_0 = 1.22$ with the angular frequency $\Omega_0 = 0.000078 \text{ s}^{-1}$. The dust grain oscillates between $r_1 \approx 0.96 R_{\text{Th}}$ and $r_2 \approx 1.22 R_{\text{Th}}$ which corresponds to the results of the numerical computations presented in Figure 5.

6. Discussion and Conclusion

We have suggested a mechanism for the filling of the Thebe extension by dust grains. Our calculations are based on the Divine model which assumes that thermal plasma in the inner magnetosphere of Jupiter is rather warm and dense, i.e., at the orbit of Thebe $T_e = 45 \text{ eV}$ and $N_e = 50 \text{ cm}^{-3}$. As a result the equilibrium electric potential on dust grains in the Thebe extension should be high, $\phi \approx -162 \text{ V}$, and the total electric charge on a micrometer-size grain is of the order of $Q_d \approx 10^3 e$. Due to such high values of the potential and the electric charge, dust grains orbiting Jupiter are almost insensitive to the solar UV radiation at the sunlit side of the planet. Hence, the mechanism of shadow resonances as suggested by Hamilton and Krüger (2008) does not work under these conditions.

According to our analysis, the dynamics of strongly charged small dust grains (fraction of a micrometer) in the vicinity of Thebe's orbit can be quite different depending on the initial conditions. Small dust grains

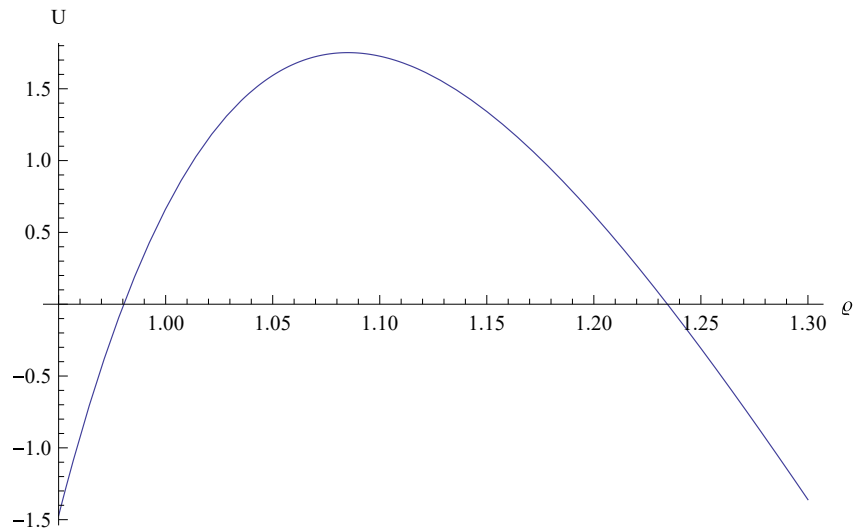


Figure 6. Distribution in space of the potential U for a small dust grain ($a = 0.3 \mu\text{m}$) with an equilibrium electric charge. The initial velocities are the same as in Figure 5. On the horizontal axis the dimensionless coordinate r/R_{Th} is given. The region with $U > 0$ corresponds to the range of radii where the dust grain oscillates.

ejected from Thebe even with a rather high radial velocity only slightly penetrate into the Thebe extension and later on gradually migrate into the Thebe ring. Examples of radial oscillations for grains with different masses are presented in Figures 3 and 4. At the same time, negatively charged small grains starting their motion in the Thebe extension remain there for a long time oscillating between two turning points r_1 and r_2 . The corresponding example is presented in Figure 5. The positions of these turning points depend on the initial conditions with which a given small grain starts its motion (radial position and initial velocities). For example, if a small grain ($a = 0.3 \mu\text{m}$) starts from a large dust grain due to fragmentation at $r_0 = 1.22R_{\text{Th}}$ with the radial velocity and the azimuthal frequency which coincide with the corresponding parameters of a large grain ($V_r = 2.8 \text{ km s}^{-1}$, $\Omega_0 = 0.000078 \text{ s}^{-1}$), it oscillates in the equilibrium case between $r_1 \approx 0.96 R_{\text{Th}}$ and $r_2 \approx 1.22 R_{\text{Th}}$. This means that such grain penetrates rather deep into the Thebe extension (up to approximately 50,000 km).

Our results have a quite clear physical meaning. Assume that an additional moon U orbits Jupiter at some distance $R_U > R_{\text{Th}}$. At the moment $t = 0$, a small dust grain is ejected from this moon and begins to move with some negative electric charge. It was shown by Horányi and Burns (1991) that negatively charged grains ejected outside the synchronous orbit of Jupiter oscillate at radial distances slightly less than the orbit of the moon. In our case, a large dust grain plays the role of an additional moon. As shown in Figure 5, if the angular velocity of a small dust grain coincides with that of a large grain (the moon U), after some time it oscillates at radial distances slightly less than the instant radial distance of the large grain at $t = 0$. Only at the beginning due to its finite initial radial velocity, the small grain makes somewhat larger radial excursions. As for large grains, they are weakly influenced by the corotating electric field due to the small ratio of their electric charge to mass Q_d/M_d . At the same time, it is important to note that we have considered the case when large dust grains were ejected from Thebe with a non-zero velocity component parallel to the angular velocity of Thebe. This additional velocity stems from the ejection of the particles from Thebe's surface. Due to this, equilibrium orbits for such grains are shifted toward larger radial distances which is supported by numerical modeling (see Figures 1 and 3).

As mentioned before, the equilibrium electric charge on a dust grain in the Thebe extension should be high. Hence, the local electric field in the vicinity of such a grain is also high. After ejection of a grain from the surface the electric charge and the electric field grow in magnitude, approaching their equilibrium values (see Figure 2). If a large grain is porous it might disintegrate into smaller fragments in case the electric force becomes strong enough (i.e., the electrostatic stress exceeds the tensile strength), see, for example, Böhnhardt and Fechtig (1987) and Stark et al. (2015). Rather crude estimates confirm that the electric disruption could be efficient in filling the Thebe extension with small dust grains. Note that such a process should

operate also in the gossamer rings. The other sources of small dust grains in the Thebe extension are plasma sputtering, mutual collisions of large grains, and their collisions with micrometeorites. All these processes are slow in comparison with the electric disruption. Note that due to electric disruption tiny grains (hundreds and tens of nanometer) could appear, see Böhnhardt and Fechtig (1987) and Stark et al. (2015). This means that not only Io is a source of tiny grains in the inner magnetosphere of Jupiter (as it was discussed by Grün et al., 1998) but also electrostatic disruption of rather large negatively charged dust grains can occur in the vicinity of Thebe's and Amalthea's orbits about Jupiter.

So far, the measurements by the Juno spacecraft probe the Jovian magnetosphere only down to $R \approx 10 R_J$, showing that the ion concentrations strongly increase toward Jupiter (Kim et al., 2020). In the future, Juno will hopefully provide us with measurements of charged particles much closer to Jupiter that will allow us to better constrain the physical processes driving dust particle motion in the Thebe extension.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this article. The data we are referring to in the manuscript have been published elsewhere and the appropriate references are given in the text.

Acknowledgments

N. Borisov likes to thank the Max Planck Institute for Solar System Research (MPS) for supporting his visits at MPS during which a significant part of the work for this manuscript was performed. Open access funding enabled and organized by Projekt DEAL.

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