CHARGED DUST IN THE OUTER PLANETARY MAGNETOSPHERES

III. Satellite Impact Geometries

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Abstract. Interplanetary dust grains entering the Jovian plasmasphere become charged, and those in a certain size range get magneto-gravitationally trapped in the corotating plasmasphere. The trajectories of such dust grains intersect the orbits of one or more of the Galilean satellites. Orbital calculations of micron sized dust grains show that they impact the outermost satellite Callisto predominantly on its leading face, while they impact the inner three – Io, Europa and Ganymede – predominantly on the trailing face. These results are offered as an explanation of the observed brightness asymmetry between the leading and trailing faces of the outer three Galilean satellites. The albedo of Io is likely to be determined by its volcanism.

1. Introduction

In a recent paper (Hill and Mendis, 1979; Paper I), we considered the charging of interplanetary dust grains entering the Jovian magnetosphere, and the resulting physical effects such as electrostatic disruption. In a subsequent paper (Hill and Mendis, 1980; Paper II) we considered the evolution of these charged dust fragments. In particular we showed that due to the velocity induced modulation of the surface potentials, grains of certain sizes (radius $> 0.2\,\mu$) can lose energy and be magneto-gravitationally captured to form a dust disc in the equatorial plane. We considered the evolution of these grain fragments, projected at various angles from a distance of 35 Jovian radii from the planet, and showed that the resulting distribution was in very good agreement with the observations from the Pioneer and Voyager spacecraft. We also briefly discussed the impact geometries of these grains on the Galilean satellites, and noted that they are likely, on the average, to hit the outer satellite on the leading face, and the inner satellites on their trailing faces, giving rise to the observed brightness asymmetries in these synchronously rotating satellites.

The excellent, subsequent Voyager observations have produced an increased interest in this problem, and Wolff and Mendis (1981) recently considered the role of the corotating plasma impaction on darkening the trailing faces of all the atmosphere-free Jovian satellites. In this paper, we consider the problem of impact geometries of charged dust fragments on the Galilean satellites in detail, and we estimate their impact rates on the leading and trailing hemispheres of the satellites. We show that this charged dust impaction, taken independently or together with plasma impaction, could explain the observed brightness asymmetries.

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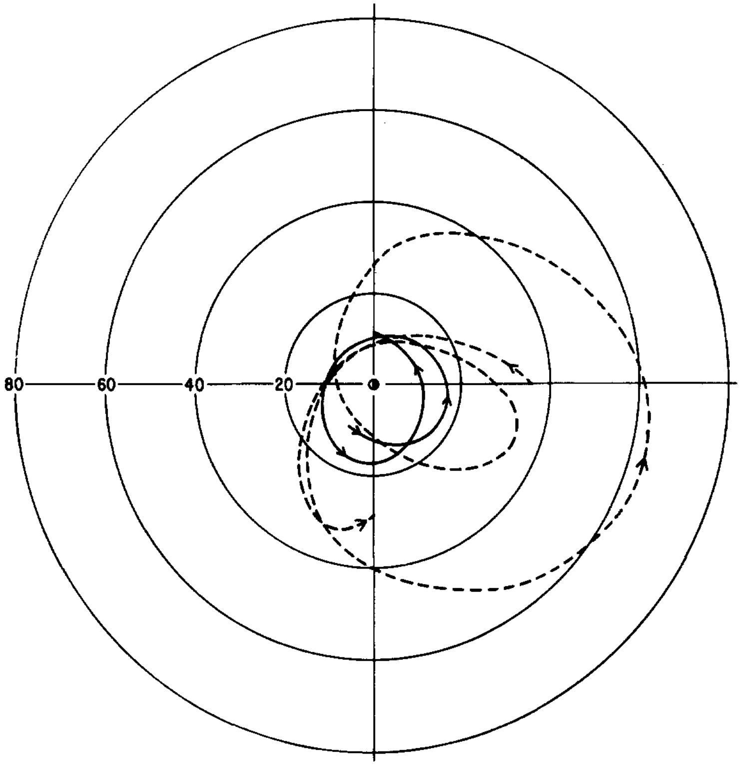

Fig. 1. Initial orbit of 1.5 μ dust grain with initial velocity vector aimed 45° prograde at escape speed at a distance of $35 R_J$ (broken line). The inner loops (solid line) show the orbit after 200 d.

The trajectories of dust grains entering the plasmasphere have been calculated by integrating the equations of motion (Paper I) using a 5th order Runge–Kutta method. A simple model consisting of a thermal plasma at constant temperature ($kT = 400$ eV) and density of 1 electron per cm^3 was used for the plasmasphere, which is corotating with Jupiter to a distance of 35 Jovian radii. The magnetospheric magnetic field used is described in Paper I.

2. Impact Geometry

Dust grains smaller than about 1.5 to 2 μ radius become trapped in the Jovian plasmasphere. Figure 1 shows the trajectory (dashed line) of a 1.5 μ grain immediately after entering the plasmasphere at a 45° prograde angle. As pointed out in Paper I, the phase lag between the oscillating potential and the orbital radius during the particle motion (see Figure 5, Paper I) results in a loss of orbital energy. After one large loop out to about 60 Jovian radii, the grain becomes trapped and continues to lose energy. A single revolution of the grain after 200 d is shown by the solid curve. Figure 2 shows the Jovian distance of the grain as a function of time for 200 d. The solid lines are plotted through the envelope of the apojove and perijove distance. Since the apojove and perijove approach a common

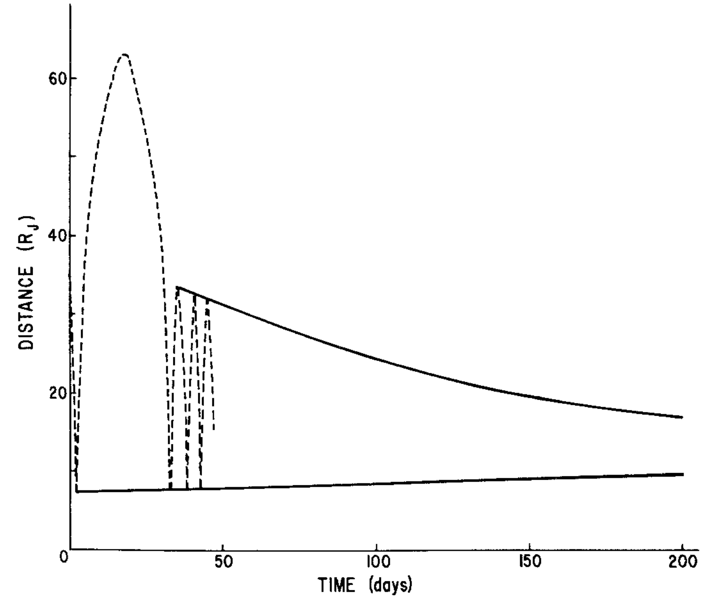

Fig. 2. Orbital radius (broken line) and its envelope (solid line) as a function of time for 1.5 μ dust grain with initial velocity vector aimed 45° prograde.

distance, the orbit eventually evolves into a circle. The final fate of such a grain in a circular orbit must be considered undetermined by the present calculations. Solar radiation pressure reduces the size of such orbits (Paper II) while sputtering (collision by high energy proton) tends to destroy the grain in a matter of decades. Those dust grains whose orbits cross the orbit of a Galilean satellite may of course suffer a collision with the satellite and be lost. As was shown in Paper II, grains not smaller than about 0.2 μ in radius have variable potentials and can become trapped in the plasmasphere. Grains whose radii are smaller than about 0.2 μ will have a constant potential, limited by field emission, and will therefore move in perfectly periodic orbits. We shall examine the motion of a 1 μ radius grain in detail.

The first revolution of the grains launched at 80° prograde (Figure 3) and 80° retrograde (Figure 4) are shown as dotted lines. One revolution of these grain orbits after 100 d is also shown in the two figures by solid lines. The motion of the prograde grain is initially a large loop which gradually evolves into a more circular loop after 100 d, and eventually into nearly circular orbit after more than 400 d. Grains in retrograde motion have orbits with tight loops near Jupiter both initially and after 100 d. It takes these grains more than 400 days to evolve into retrograde circular orbits close to Jupiter. To determine whether the grain impacts the leading or trailing face of a satellite, we compare the azimuthal velocity of the grain at the satellite's orbital distance with the Kepler velocity. The orbits corresponding to a fan of launch angles were calculated in order to obtain an estimate of the relative number of leading and trailing satellite face impacts by

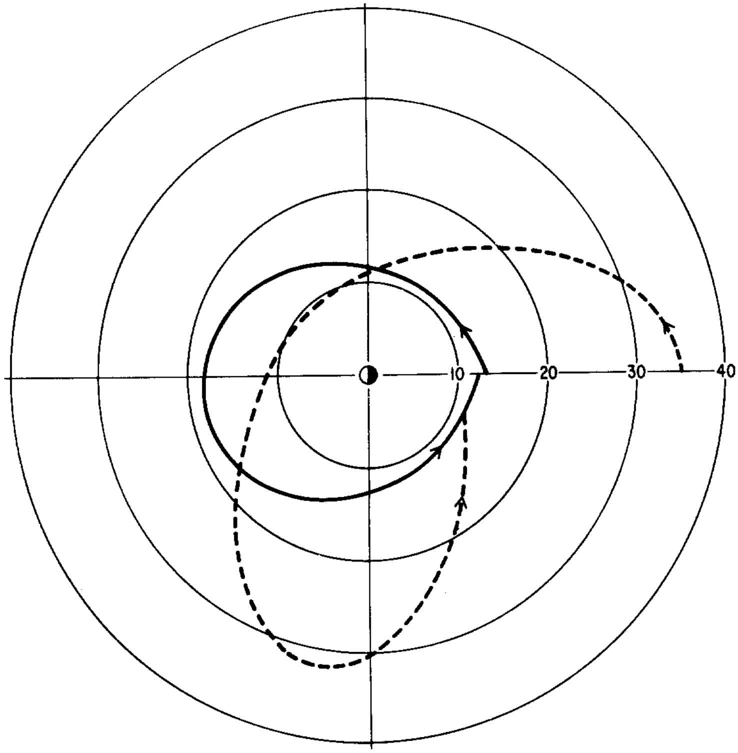

Fig. 3. Initial orbit of 1 μ dust grain with initial velocity vector aimed 80° prograde at escape speed at $35 R_J$ (broken line). The inner loop (solid line) shows the orbit after 100 d.

dust particles. This is equivalent to assuming an isotropic distribution of launch angles in the equatorial plane at the plasmapause. Trajectories were calculated in 20° steps starting at 80° prograde through 80° retrograde. The dust grain coordinates and velocities were sampled at 12 hr intervals to determine the relative number of leading and trailing satellite face impacts for each angle. Grains within 0.5 Jovian radii of a satellite were assumed to collide with the satellite. (Selection of a smaller value for their distance would have required a considerably larger computing time). The results of the first 100 d of dust grain impacts are shown in Figure 5.

Retrograde grains lose energy rapidly, causing their apojoves to decrease rapidly. These grains are removed from the neighborhood of Callisto and Ganymede, while prograde grains are still crossing the orbit of Ganymede. In the simulation Callisto had 6 impacts on the leading face, corresponding to launch angles between 90° retrograde and about 38° prograde, and 3 on the trailing face corresponding to launch angles greater than about 38° prograde. Although not shown in the figure, both leading and trailing impacts on Callisto result from dust grains launched around 38° in the prograde direction. These grains initially impact the leading face of Callisto, but after orbital evolution impact the trailing face. Let this angle be called the cross-over angle. If the plasmapause was exactly

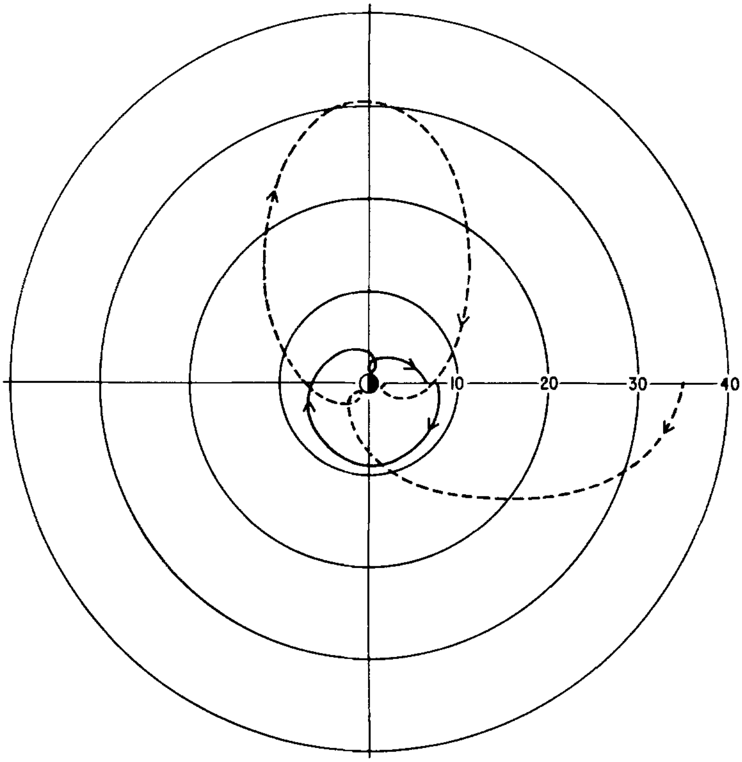

Fig. 4. Orbit of 1 μ dust grain with initial velocity vector aimed 80° retrograde at escape speed at $35 R_J$ (broken line). The inner loop (solid line) shows the orbit after 100 d.

at the orbit of Callisto, geometrical considerations show that the cross-over angle is 45° prograde. This results from the escape velocity being $\sqrt{2}$ times the circular velocity, which is also the secant of 45°. If we assume that grains enter in a uniform angular distribution in the plane of the equator, those from 90° retrograde through 45° prograde (135°) impact the leading face, while those from the remaining 45° impact the trailing face. This would mean that about 3/4 of the grain impacts would be on the leading face, as opposed to about 2/3 when the plasmapause was at 35 Jovian radii. On the other hand, if the plasmapause was at 60 Jovian radii, the cross-over angle is 28° prograde, which also corresponds to about 2/3 of the impacts on the leading face. Thus there is a predominance of leading face impacts on Callisto for all sizes of the plasmasphere.

During the first 100 days Ganymede had 39 leading face impacts and 34 trailing, Europa had 93 leading face impacts and 43 trailing, and Io had 79 leading face impacts and 43 trailing. While this would indicate that indeed all four satellites are preferentially impacted on the leading face, we will show that this is not the case for the inner satellites, when the simulation is extended considerably beyond 100 d. The calculation of all grain orbits has been extended to as much as 800 d, to estimate the long term distribution of the impacts. The grain orbits with initial velocity vectors in the retrograde direction

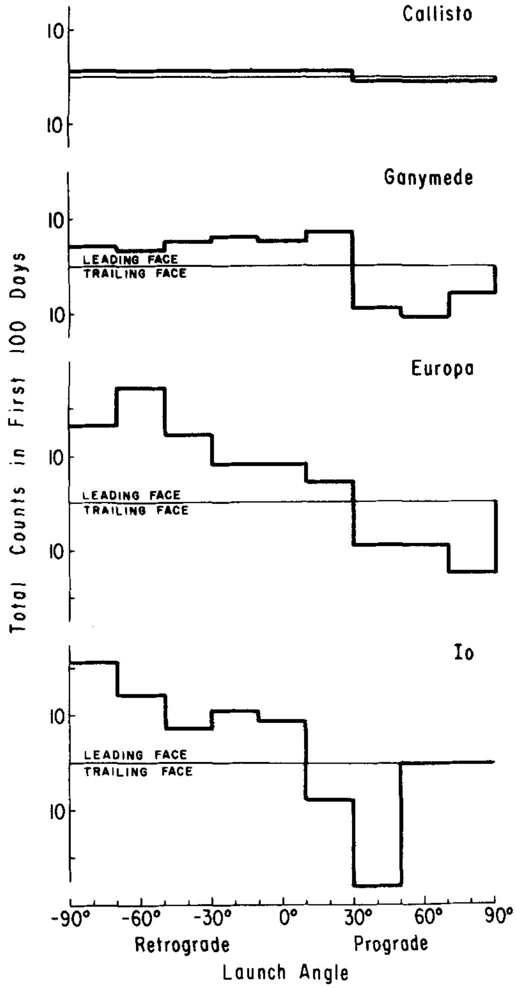

Fig. 5. Histogram of simulated impact counts after 100 d on leading and trailing faces of the Galilean satellites. Leading face impacts are shown as positive and trailing face impacts are shown as negative.

evolve rapidly toward Jupiter and after less than 230 d are removed from the population impacting these satellites. The prograde grains, having larger perijoves, remain in the range of 6 to 16 Jovian radii for a much longer time. The dust grain perijove and apojove distances after 10, 100, and 400 d are shown as a function of initial velocity angle in Figure 6. Retrograde grains which impact the leading face of Europa move within Europa's orbit after about 100 to 230 d (depending on launch angle) while some grains with launch angle near 48° prograde impact the trailing face of Europa for more than 800 d. Figure 6 shows that the prograde grain orbits eventually evolve into circles with radii ranging from 1.3 to 14 Jovian radii. Since all grains launched at 33° prograde at 35

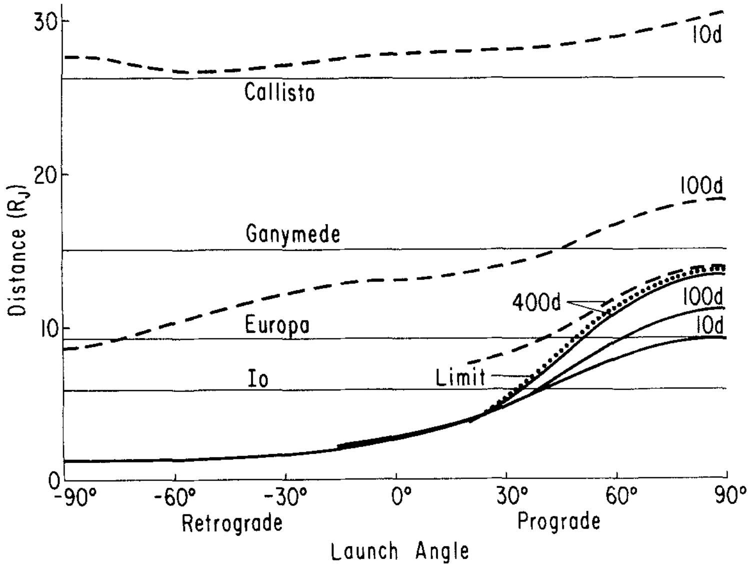

Fig. 6. Apojove (dashed lines) and perijove (solid lines) after 10, 100, and 400 d as a function of initial velocity vector angle. The dotted line indicates the position which the apojove and perijove are approaching after an extended time period.

Jovian radii converge on Io, and those at about 48° prograde converge on Europa, we expect these inner satellites to be bombarded primarily on the trailing face by these grains. If the time covered by Figure 5 were extended indefinitely, we would technically have 'singularities' in the histograms at these angles.

The final results of the impact simulation are shown in Figure 7. The time interval has been extended to as much as 800 d and the sampling interval reduced to 4 hr. Also, impact counts on Europa were estimated at 2° intervals near the singularity angle, 48° prograde. Impacts were counted in this interval (40 to 60° prograde) when grains were within 0.1 Jovian radii, and the results were multiplied by 5 to bring the count into scale with the rest of the simulation. This increased resolution displays the singularity in the Europa impacts at 48° prograde and allows an approximate integration of the relative number of leading and trailing impacts. Since grains launched at about 80° to 90° prograde converge to 13.6 Jovian radii, just inside the orbit of Ganymede (15 Jovian radii), we find a predominance of trailing face impacts on Ganymede similar to that of Europa. The approximate integrated impact count ratios, leading face/trailing face, are 489/995 for Europa, 145/289 for Ganymede and 35/19 for Callisto. The fractions are left unreduced to show the relative counts for the satellites. However, they are seen to be about 1/2, 1/2, and 2/1. Io was not included in the extended calculation since its albedo is likely determined by volcanic processes rather than micrometeor impacts. However, the presence of the singularity in the trailing face distribution results in its dominance for impacts on satellites located between 1.19 and 13.6 Jovian radii. The grains launched at

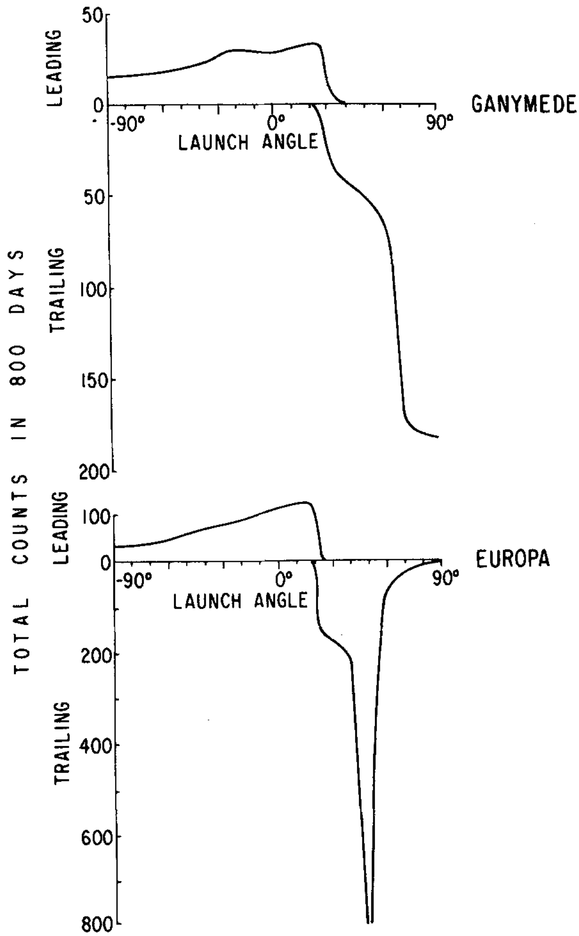

Fig. 7. Smoothed histogram of impact counts at 4 hr intervals for up to 800 d showing the effect of the 'singularity' angles on the impact counts of grains converging on the trailing face of Europa and Ganymede. Leading face impact counts are shown as positive and trailing face impact counts are shown as negative.

angles greater than 25° prograde have perijoves which increase with time and approach the dotted curve labeled 'limit' in Figure 6. Grains launched at less than 25° prograde show a small decrease in their perijove approaching a limit slightly below the 100 day curve. The perijove limit has been determined by extrapolation. The minimum perijove limit is 1.19 Jovian radii for grains launched at 90° retrograde.

3. Discussion

Ground-based observations of the Galilean satellites show regular variations in brightness associated with the orbital phase. Callisto is 15% darker on its leading side than on its trailing side, while Europa and Ganymede are 15%–25% darker on their trailing sides than on their leading sides. In Paper I we used preliminary results of the dust orbit calculations, to explain this observation as a result of nonsymmetric dust impacts on the satellites. The present calculations show a definite preference for leading face impacts on Callisto and trailing face impacts on Europa and Ganymede. More recently, Wolff and Mendis (1981) have examined the magnetospheric plasma interactions with the satellites and determined the net effect to be a darkening of the trailing faces of all the satellites. The reversal of the darkening for Callisto, therefore, cannot be explained on the basis of plasma impacts alone, and seems to require the process we have described to overcompensate to it. The innermost Galilean satellite Io is not considered in the above discussion since its surface is continually being changed by the volcanic activity. For Europa and Ganymede the effect of the micrometeor impacts is clearly in the same sense as the plasma in darkening the trailing face.

In conclusion, it needs to be stressed that the calculations presented here, as well as those in Papers I and II, were performed on the basis of a simplified model of the thermal plasma in the Jovian magnetosphere. For instance, while the energy (kT) of the thermal plasma increases to several hundred eV in the outer magnetosphere, it is significantly smaller inside $10R_j$, and becomes very small ($kT \leqslant 10$ eV) in a toroidal region around Io. A proper calculation of the charged grain trajectories and their evolution should take this into account. Furthermore, due to the tilt of the axis of rotation to the magnetic moment vector and the associated warp in the plasma sheet, a proper calculation of these trajectories should not constrain them to the equatorial plane, as we have done. Enough is now known about the magnetic field and plasma distribution in the Jovian magnetosphere for a more reliable numerical simulation of the trajectories of interplanetary grains entering the Jovian magnetosphere at any latitude. We intend to address this problem in the near future. The main aim of this paper, and the other two in this series, has been to focus on the physical and dynamical processes of charged dust grains using a simple model of the Jovian magnetosphere. Despite this limitation, it is indeed gratifying that the present analysis has been able to reproduce rather well the observed overall dust distribution in the equatorial plane including the thin dust ring at a Jovicentric distance $\leqslant 2R_j$. Furthermore, the charged dust impact geometries on the Galilean satellites predicted by this simple model are exactly in the right sense to produce the observed brightness asymmetries between their leading and trailing faces. We are therefore inclined to believe that we have identified the basic physical and dynamical processes associated with the injection and evolution of charged dust orbits in the Jovian magnetosphere.

Acknowledgments

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