CHARGED DUST IN THE OUTER PLANETARY MAGNETOSPHERES

II. Trajectories and Spatial Distribution

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Abstract. In this paper we consider the dynamics of the electrostatic disruption products of fragile interplanetary dust aggregates which are initially electrically charged on entering the Jovian plasmasphere. On account of their large specific charges, these small dust fragments are strongly effected both by the Lorentz electric force as well as by the polarization electric force resulting from the co-rotation of the Jovian plasmasphere. The detailed orbits of these charged dust fragments, which are shown to be confined to the equatorial plane, are computed for various launch angles. It is established that the fragments with radii typically around $1\,\mu$ are magneto-gravitationally trapped within the plasma sphere due to the velocity induced oscillation of their surface potentials. The spatial distribution of these fragments are evaluated and the time evolution of the distributions followed. On this basis it is argued that the distribution of micrometeoroid dust within the Jovian magnetospheres, observed by the Pioneer 10 and the recent Voyager spacecraft, is a result of this magneto-gravitational trapping and subsequent orbital evolution of these charged dust fragments. Our discussion includes both the sudden increase, by over an order of magnitude, of the micrometeoroid dust flux at about $30R_J$ observed by Pioneer 10, and the thin inner dust ring recently observed by the Voyager spacecraft. The observed brightness asymmetries between the leading and trailing sides of the Galilean satellites appears to be a natural consequence of the impact geometries of these charged dust grains with the satellite surfaces.

1. Introduction

In an earlier paper (Hill and Mendis, 1979; hereafter referred to as Paper I), we discussed the physical and dynamical processes associated with the entry of interplanetary dust grains into the magnetospheres of the rapidly spinning outer planets, particularly that of Jupiter, whose magnetic and plasma environment is reasonably well known since the first *in situ* measurements with Pioneer 10.

It was shown that, the grains, on reaching the outer edge of the co-rotating Jovian plasmasphere at a distance of about $35R_J$ get rapidly charged to numerically large negative potentials of about -670 V on the dayside and -830 V on the nightside if they could avoid electrostatic disruption. (This is in contradistinction to what happens if the terrestrial magnetosphere, where grains can get charged to comparably large negative potentials on the nightside, but attain small positive potentials (~ 1 V) on the dayside).

It was assumed that these interplanetary grains were typically fragile aggregates of the Brownlee type, and it was shown that they disrupted electrostatically to their smallest fragments long before achieving these steady state potentials. For instance, a parent grain of radius $R_g \simeq 20\,\mu$ reached a critical potential $\Phi_c \simeq -220$ V within a time of

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about 4 min, whereupon it got disrupted to its constituent crystalline grains of presumably much larger tensile strength. Limiting ourselves to the equatorial plane of the planet, we established that these negatively charged fragments were strongly attracted towards the planet by the (radial) co-rotational electric field produced by plasma polarization in the plasmasphere, and that some get stably trapped. Finally, we suggested that the sudden enhancement by over an order to magnitude of the interplanetary dust flux measured by Pioneer 10 at about $30R_J$ from Jupiter resulted from a combination of these two aforementioned effects; namely, electrostatic fragmentation of fragile grain aggregates entering the magnetosphere, and the subsequent magnetogravitational capture or focusing of the resulting charged fragments, while also increasing their orbital speeds within the magnetosphere.

In this paper, which is a sequel to Paper I, we will calculate the detailed orbits of these grain fragments of different sizes, launched at different angles from the point of disruption of the parent grain. The time evolution of their spatial distributions will be evaluated and comparison will be made with the one produced by pure gravitational focusing. The computed dust orbits will clearly indicate how they impact the surfaces of the inner and outer Galilean satellites and lend support to the argument (Mendis and Axford, 1974) that the observed brightness asymmetries between their leading and trailing sides are a natural consequence of this impact geometry. Further confirmation of this will have to await detailed analysis of the high quality observations of the Galilean satellites from the Voyager missions. Firstly, however, we will discuss the question of charge redistribution among the grain fragments during the electrostatic disruption process, since this was not adequately considered in Paper I.

2. The Redistribution of Electric Charge During Grain Fragmentation

In Paper I, it was seen that while the time taken by a small grain to charge up to its equilibrium potential varied inversely with its radius, the actual time for a grain of radius $1\,\mu$ was as much as 10 h. This time is very much larger than any conceivable time scale for the electrostatic disruption of grains, which may presumably be just a small fraction of a second. Consequently, we can assume, to a very large degree of accuracy, that the total electric charge on the grain is conserved during the disruption process. Furthermore, since the charge resides only on the surface, only those fragments which originate from the outermost layer of the parent grain will share its surface charge. Those fragments which come from the inside still start off essentially with zero charge and potential.

We can proceed to make an estimate of the potential of these outermost fragments in the following way. Suppose the parent grain of radius R_g is an aggregate of spherical daughter grains, all of radius R_f. Then the number of daughter grains in the outer shell of thickness $2R_f$ (which share the total charge $Q_g = \Phi_g R_g) \simeq 6(R_g/R_f)^2$. Consequently, the charge per outer fragment $\simeq \Phi_g R_f^2/6R_g$, and their common potential $\Phi_f \simeq \Phi_g R_f/6R_g$. With $\Phi_g \simeq -220\,\text{V}$, $R_g \simeq 20\,\mu$ and $R_f \simeq 1\,\mu$, we get $\Phi_f \simeq -2\,\text{V}$. For smaller values of R_f, Φ_f is correspondingly (numerically) smaller. Consequently, for all practical purposes,

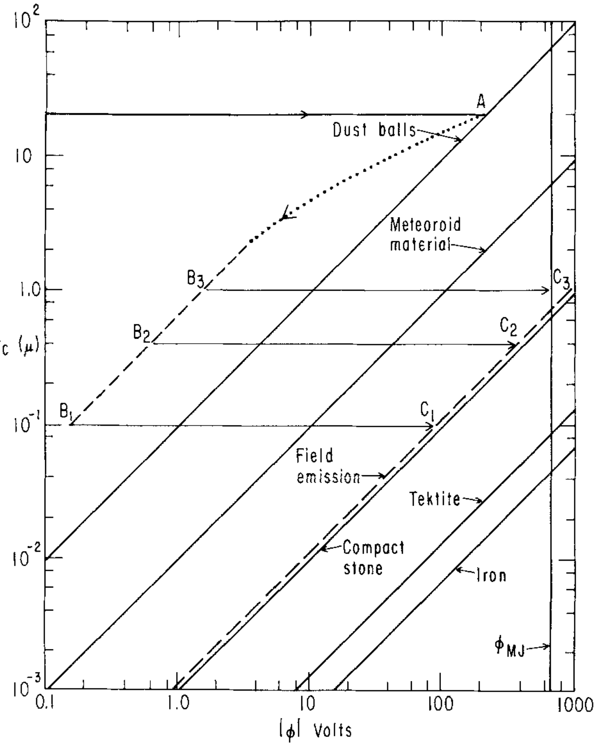

Fig. 1. Critical grain radii for the electrostatic disruption of different materials; the stable regions being above the respective lines. The field emission limit is shown by the broken line, while the charging paths of the parent grain and its disruption fragments are shown by the horizontal lines.

we may assume that the disruption fragments start off essentially with zero potential. The variation of $|\Phi|$ for 3 outer fragments of different sizes are shown by the horizontal lines in Figure 1. All inner fragments, of course, will start with $\Phi = 0$. As discussed in Paper I, the solid diagonal lines indicate the critical radii of grains of different material against electrostatic disruption at different potentials, with the stable regions above the respective lines. The critical radii for grains against field emission is represented by the broken diagonal line, with region stable against discharge by this process being above the line. Here a Brownlee type grain aggregate, assumed to have the tensile strength of a loose dust ball ($\simeq 10^4$ dyne cm^{-2}), charges up to about -220 V (point A) on entering the Jovian magnetosphere, the process taking about 4 min. It then bursts into its constituent particles, which are assumed to have a much greater tensile strength (e.g., that of compact stone). As discussed earlier, all the resulting fragments will start off with zero or negligible (negative) potential. Fragments of radii 0.1 μ and 0.4 μ will recharge to potentials of -92 V and -360 V, respectively (points C_1 and C_2); these limits being set by field emission. The times required to attain these potentials are quite large on account of the small sizes of the fragments being, respectively, about 1 h and 0.5 h. A larger fragment of radius 1 μ will charge up to the potential determined by the plasma and radiative environment in the magnetosphere, which is about -670 V on its dayside (point C_3). The time required by the grain fragments to attain this potential is likewise quite large, being about 2 h.

3. Trajectories of the Charged Dust Fragments

In this section we will proceed to evaluate the orbits of these charged dust fragments. It was shown in Paper I that the Jovian magnetosphere is expected to co-rotate up to about $35R_J$. In this co-rotating region, the equation of motion, in a planet-centered inertial frame, of a charged grain is

$$m\ddot{r} = \frac{q(t)}{c}[-(\mathbf{\Omega} \times r) + \dot{r}] \times B(r) - \frac{GM_J m}{r^3} r - F(r), \quad (1)$$

where m and $q(t)$ are, respectively, the mass and the varying change on the grain; M_J, $\mathbf{\Omega}$ and $B(r)$ are, respectively, the mass, angular velocity and magnetic field of the planet, and $F(r)$ is the Coulomb drag on the grain, which was shown to be negligible in Paper I. Here the term $-(\mathbf{\Omega} \times r) \times B(r)$ represents the plasma polarization electric field induced by the co-rotation of the magnetosphere.

The most recent Voyager 1 observations have shown that the thermal plasma co-rotates strictly only in the inner region ($r \lesssim 10R_J$) of the magnetosphere. Beyond that, there is a systematic decrease up to about 30% in the outer regions (McNutt *et al.*, 1979), which may be associated with plasma convection and the associated spiraling of the magnetic field. In this paper we will neglect this effect. Its inclusion will change the nature of the computed orbits somewhere but will not alter the eventual grain distributions since the polarization electric field still has a large-radial component in the outer regions of the magnetosphere while being strictly radial in the inner region where the grains are shown to eventually congregate.

As in Paper I, we confine ourselves to the equatorial plane of the planet. This is because, on the one hand, the semi-thickness of the magnetodisc plasma distribution beyond $r \gtrsim 15R_J$ is only about $1R_J$ (Frank *et al.*, 1976), while on the other, any negatively charged grain moving at a grazing incidence to this plane and attempting to leave it will be pulled back towards it by the normal component of the electric field experienced in the magnetodisc. We will (for mathematical simplicity) assume that the spin axis and the magnetic dipole axis are centered at the planet and are exactly parallel (although in reality the dipole axis is displaced by about $0.2R_J$ from the center and tilted at an angle of about 10° to the spin axis (Smith *et al.*, 1974; see also Paper I). Choosing the z-axis parallel to $\mathbf{\Omega}$, the equations of motion in the equatorial (xy) plane is given by:

$$\ddot{x} = \frac{q(t)}{mc}(\dot{y} - x\Omega)B_z - \frac{GM_J}{r^3}x,$$

$$\ddot{y} = \frac{-q(t)}{mc}(\dot{x} - y\Omega)B_z - \frac{GM_J}{r^3}y, \tag{2}$$

where $r = (x^2 + y^2)^{1/2}$.

Since the magnetic moment and $\mathbf{\Omega}$ are assumed to be parallel, we have

$$B_z = -B_0 R_J^3 \left(\frac{1}{r^3} + \frac{1}{r_0^2 r}\right), \tag{3}$$

where $B_0 \simeq 4G$ and $r_0 \simeq 30R_J$ (Hill *et al.*, 1974; see also Paper I). The second term on the right-hand side of Equation (3) represents the drawing out of the Jovian magnetic field by the centrifugal stresses of the co-rotating plasma in the outer magnetosphere ($r \gtrsim 20R_J$) to form a thin magnetodisc.

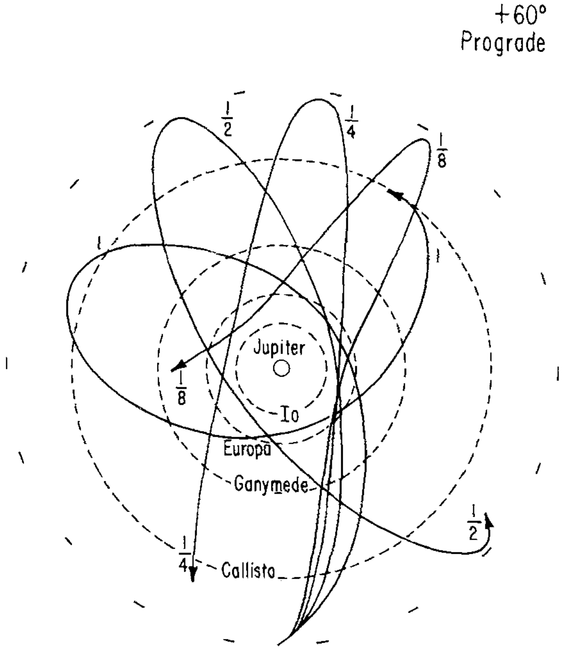

Fig. 2. Orbits of the fragments of a parent grain that enters the Jovian magnetosphere at $35R_J$ at an angle of $60°$ away from Jupiter in the prograde direction.

It was shown in Paper I, that whichever way the electrostatic self-energy of the parent grain is redistributed among its disruption products, the extra random velocity imparted to them is negligible in comparison with the initial velocity of the incoming parent grain, which is typically around the parabolic velocity ($\simeq 10$ km s^{-1} at $r \simeq 35R_J$). Consequently, we shall assume that the initial speed and direction of all the disruption products of any given parent grain are the same as that of the parent grain just before disruption.

In Figures 2, 3 and 4 are illustrated the orbits of different sized disruption fragments

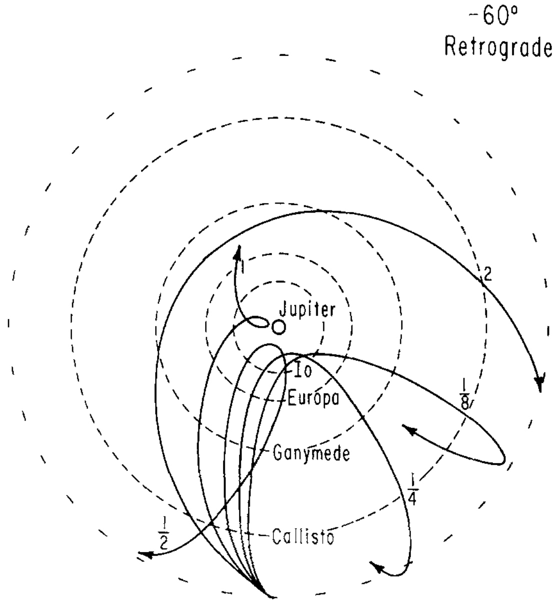

Fig. 3. Orbits of the fragments of a parent grain that enters the Jovian magnetosphere at $35R_J$ at an angle of 60° away from Jupiter in the retrograde direction.

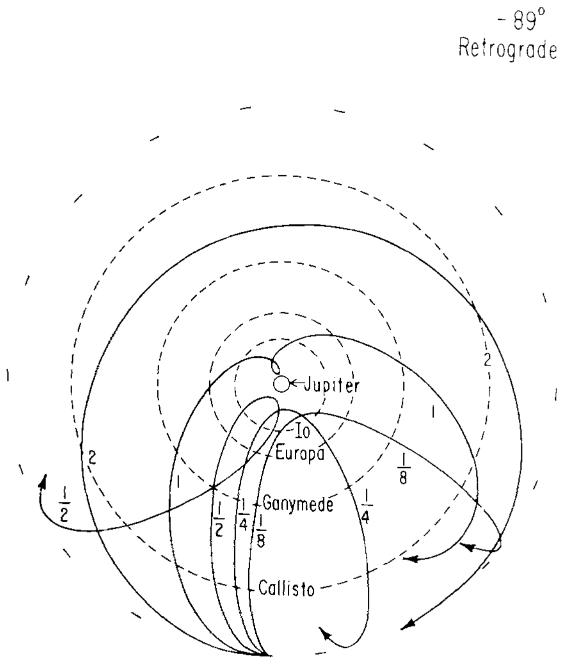

Fig. 4. Orbits of the fragments of a parent grain that enters the Jovian magnetosphere at $35R_J$ at an angle of 89° in the retrograde direction.

of parent grains entering the outer edge of the co-rotating Jovian magnetosphere ($r \simeq 35R_J$) at various representative angles. Figure 2 shows the orbits of the fragments of a parent grain which enters the magnetosphere at an angle 60° away from Jupiter in the prograde direction. It is seen that none of the fragments in the given size range of 1 μ to 1/8 μ gets within the orbit of Io. Figure 3 shows the corresponding situation when the entry angle is 60° away from Jupiter but retrograde. Here the grain fragments are pulled in closer to Jupiter by the co-rotational electric field and all except the largest one are seen to cross the orbit of Io. The 1 μ fragment does not get clear up to Jupiter. It makes a tight, high-speed loop, and ends up with a net retrograde orbit precession. The 1/4 μ and 1/8 μ fragments, however, end up with a net prograde procession as they are swept around with the plasma since they are too light to follow their own inclination as do the heavier fragments. If the entry angle of the parent grain is directly towards Jupiter (i.e., 0°), its fragments will follow orbits intermediate to the above two cases. Figure 4 shows the situation when the parent grain enters the 89° retrograde which is barely sufficient for it to get caught. Here, too, all except the largest fragment is pulled within the orbit of Io.

As we showed earlier in Paper I, the grain potentials, particularly of the larger grain fragments, are constantly changing due to their varying relative speed with respect to the co-rotating plasma. The variation of radial distance and the potential of a 1 μ sized grain fragment with time (for about 250 h) was shown in Figure 5 of Paper I. While the grain is rapidly charged up to a potential of about -800 V, it is slightly discharged at larger Jovicentric distances with a phase lag of about 6 h. This causes the non-symmetric acceleration of the fragment by the co-rotational electric field and a consequent loss in energy, resulting in trapping and subsequent shrinkage of the orbit. The grain orbit has now been integrated for almost a year and the variation of the apojove and perijove are shown in Figure 5. While the perijove remains almost constant (with only a very small increase with time during this period), the apojove shrinks all the way from $35R_J$ to less than $5R_J$ during that time.

4. The Spatial Distribution of the Dust Fragments

The distribution after one week of 1 μ sized grain fragments entering the Jovian magnetosphere at $35R_J$ pointed directly towards Jupiter (0°) is shown in Figure 6. In the computer simulation, a grain is injected every hour at $35R_J$ and hourly samples are then taken of the number of grains in each $1R_J$ thick ring from 0 to $35R_J$. The bimodal nature of the distribution is clearly a result of the longer times spent by the grains in the vicinity of their turning points. The distribution, after a period of 8 weeks, is shown in Figure 7. Energy is being continuously sapped from the orbiting grains, as discussed in the earlier section, and consequently, their apojoves are progressively moving in as they get more tightly bound to Jupiter.

The distributions associated with a retrograde injection ($-88°$) after 1 week and 8 weeks are shown in Figures 8 and 9, respectively. These are clearly similar to the two

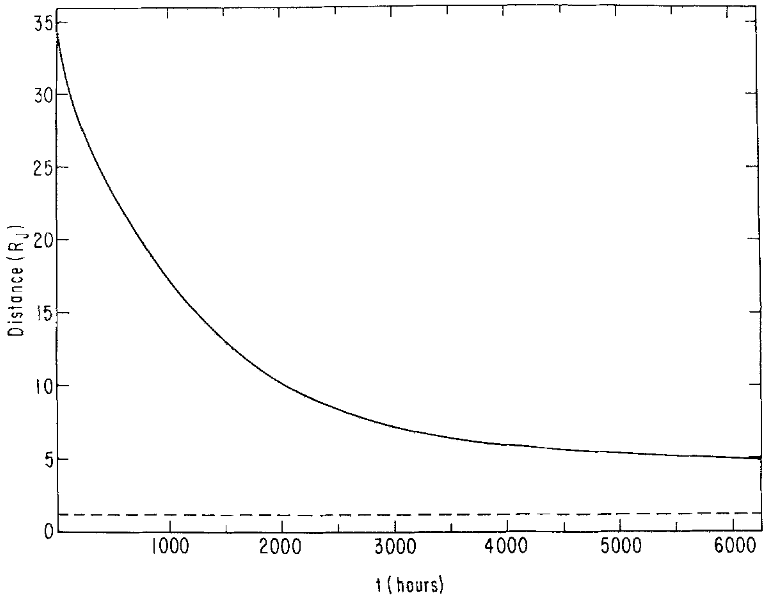

Fig. 5. The time variation of the apojove (solid line) and perijove (broken line) of a 1 μ grain, as its orbit evolves in the Jovian magnetosphere.

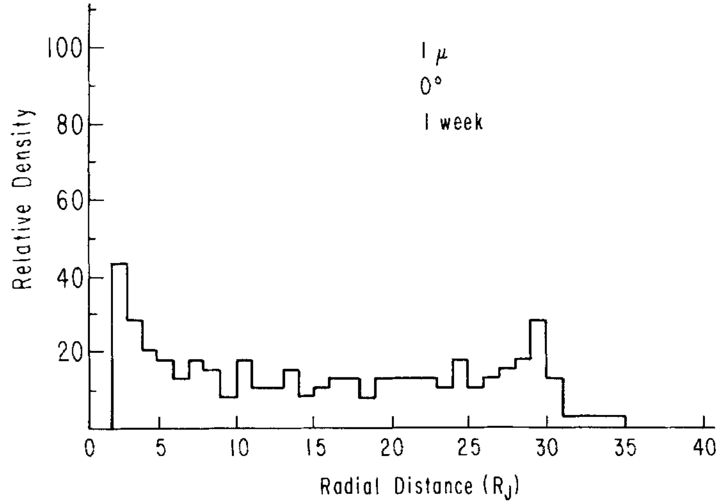

Fig. 6. Spatial distribution of 1 μ grain fragments entering the Jovian magnetosphere at $35R_J$ pointed directly towards Jupiter (0°), after one week.

earlier distributions in Figures 6 and 7 excepting that now the grains appear to have moved even closer to Jupiter after 8 weeks. We have also let this latter distribution evolve for almost 1 year with continuous injection at $35R_J$ and this is shown in Figure 10. Now we see the distribution is strongly concentrated in a ring between about $1R_J$ and

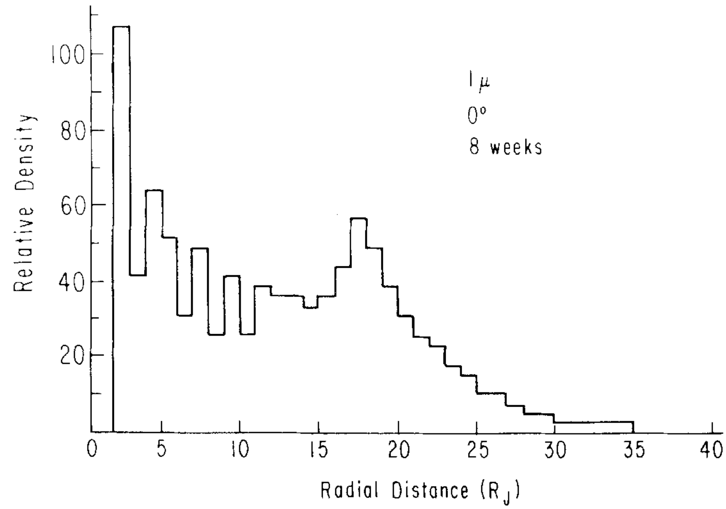

Fig. 7. Spatial distribution of 1 μ grain fragments entering the Jovian magnetosphere at $35R_J$ pointed directly towards Jupiter (0°), after eight weeks.

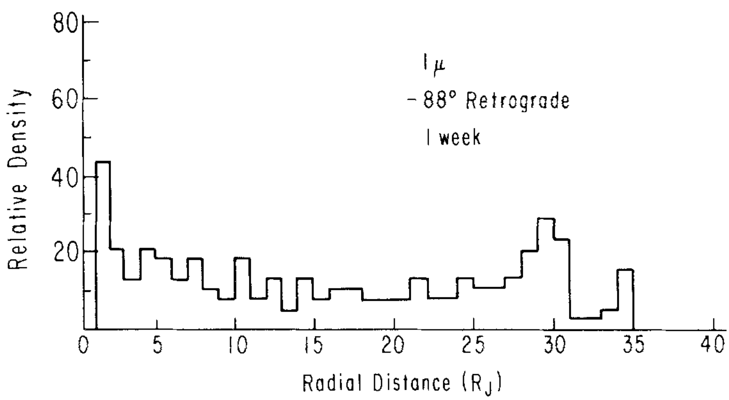

Fig. 8. Spatial distribution of 1 μ grain fragments entering the Jovian magnetosphere at $35R_J$ pointed 88° away from Jupiter in the retrograde direction, after one week.

$6R_J$ with a peak density around $5R_J$. This distribution, however, does not necessarily correspond to the one observed by Pioneer 10. The reasons being: (a) the spacecraft motion and detector orientation are ignored and (b) the detection threshold, which is strongly dependent on the relative velocity between the grains and the spacecraft, is not considered (see the discussion in Section 5).

The evolution of the distribution was initially rapid but gradually slowed down with time. This was because the relative velocity induced fluctuation of the grain potential which caused their orbits to shrink became smaller as the grain orbits shrank. Due to the rapidly increasing computer time, we were forced to terminate the numerical calculation after one year of evolution of the model distribution. It is, however, clear that

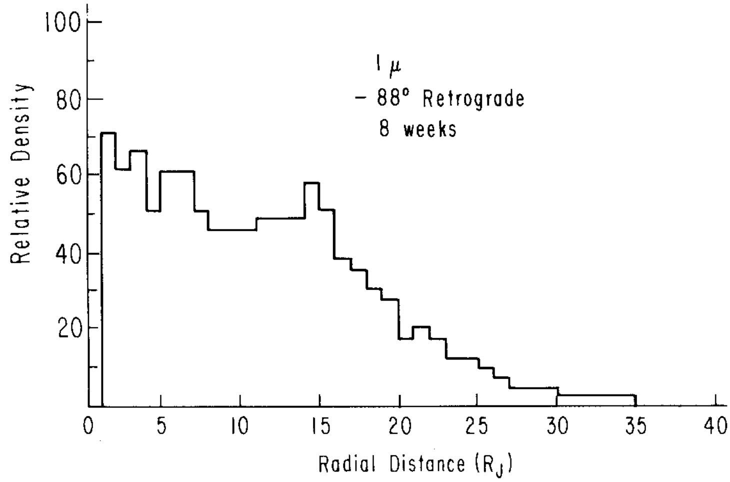

Fig. 9. Spatial distribution of 1 μ grain fragments entering the Jovian magnetosphere at $35R_J$ pointed 88° away from Jupiter in the retrograde direction, after eight weeks.

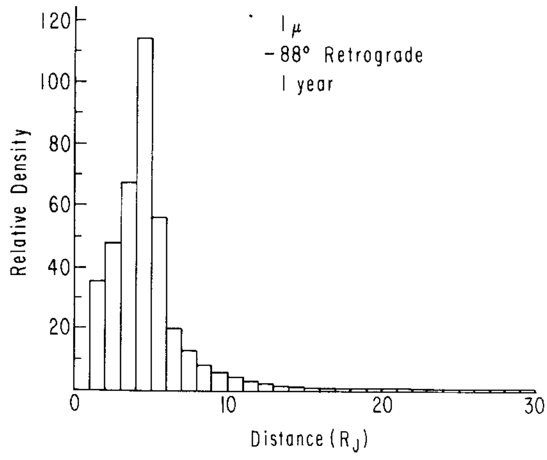

Fig. 10. Spatial distribution of 1 μ grain fragments entering the Jovian magnetosphere at $35R_J$ pointed 88° away from Jupiter in the retrograde direction, after one year.

as the evolution proceeded farther, the dust orbits would have become more and more circular, and the distribution would have tended to a more or less thin ring centered around the synchronous orbit, which is at about $2.2R_J$. This is because the co-rotation speed at this distance equals the Kepler speed, and consequently, the total electric field on the grain vanishes. The negatively charged grains moving outside this orbit will experience an electric force directed towards the planet while those moving inside it will experience an electric force directed outward.

Finally, Figure 11 shows the composite distribution after 200 h for 1 μ fragments projected at 10 different, equally spaced angles, from $35R_J$. While a few particles escape,

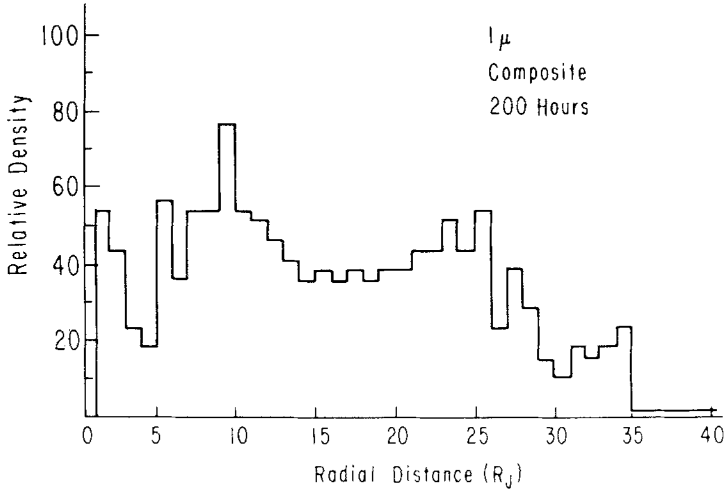

Fig. 11. Composite distribution after 200 h of 1 μ fragments projected at 10 different equally spaced angles from $35R_J$.

the rest distribute themselves in the way shown, with two broad humps. The reason for the various peaks is the discreteness of the launch angles. In reality, of course, with a continuum of injection angles, one expects a smoother distribution. With time all the distribution modes will move inward and congregate around the minimum distance. Consequently, the eventual distribution of these grains too, if they survive long enough, would be a fairly thin band with each grain moving in a more or less circular orbit.

In these calculations we have ignored the possible sinks for the grains. Some of them will, of course, eventually hit the satellites and be lost while the others move inward across these barriers. Comparison of the time scales to cross these satellite barriers with the orbital period of the satellites indicate the significant depressions will be produced in the distribution, particularly near the orbits of the inner satellites. Otherwise the overall distribution will be unaltered.

On the other hand, it was observed during the Pioneer 10 encounter that the outer Jovian magnetosphere was highly compressible and thus very sensitive to varying solar wind conditions (e.g., Simpson and McKibben, 1976). This, together with the wobbling of the plasma disc as a result of the non-alignment of the magnetic and spin axes, can cause grains to effectively leak out of the magnetosphere. Another effect that we ignored is the variation of the grain potential produced as the grain moves in and out of the Jovian shadow. Depending on the phase of the oscillation, grains may either be ejected or be more tightly bound to Jupiter. Quantitative estimates of these effects on the residence time of the grains are, however, beyond the scope of the present analysis.

We have also, so far, not considered the effects associated with solar radiation pressure on the grain orbits. There is a (variable) dynamical aberration of the solar radiation as seen by a grain orbiting Jupiter. This causes a gradual loss of angular momentum (L)

of the grain about the planet and a consequent spiraling in. Although the charged grain orbits are far from circular, as is clear for Figures 2–4, a rough estimate of the time scale of this effect can be made by assuming that the orbits (or more precisely, those of their grinding centers) remain more or less circular during the slow spiraling in. Then

$$\frac{\mathrm{d}L}{\mathrm{d}t} \simeq \frac{-L_\odot \sigma_g q}{4\pi R^2 c^2} vr\langle|\cos\phi|\rangle, \tag{4}$$

where $L_\odot$ is the solar luminosity ($\simeq 3.79 \times 10^{33}$ erg s^{-1}), σ_g is the geometrical cross-section of the grain, q is the radiation pressure efficiency integrated over the solar spectrum, R and r are, respectively, the heliocentric distance of Jupiter and the Jovicentric distance of the grain, v and ϕ are, respectively, the speed and phase angle of the grain with respect to Jupiter, and $\langle|\cos\phi|\rangle$ represents an average over one orbit. Using the fact that $L = mvr$, $v = (GM_J/r)^{1/2}$, $\langle|\cos\theta|\rangle \simeq 2/\pi$, and that typically $q \simeq 1$ for grains of radius $r_g \gtrsim 0.4\,\mu$, and integrating Equation (4), we obtain the time, t, for the grain orbit to shrink from an initial radius of r_i to the final distance of r_f as

$$t \simeq \frac{4\pi^2}{3} \frac{R_g \rho_c c^2 R^2}{L_\odot} \ln\left(\frac{r_i}{r_f}\right), \tag{5}$$

where ρ_g is the bulk density of the grain. This result is, to within a small numerical factor, identical with the one obtained by Peale (1966) by using a more detailed analysis. When $r_i \simeq 35R_J$, $r_f \simeq 2R_J$, $\rho_g \simeq 2$ g cm^{-3} and $R_g \simeq 1\,\mu$, $t \simeq 4 \times 10^5$ y.

This time scale for orbital evolution is very much larger than the one that we obtain from the electrodynamics of charged grains (~ 1 y). However, there may be a much shorter time scale perturbation on the grain orbits associated with the direct solar radiation pressure itself, as opposed to the Poynting–Robertson effect. It was first shown by Peale (1966) that solar radiation pressure would cause a large amplitude periodic oscillation of the orbital eccentricity of the dust grains in step with the apparent motion of the Sun (i.e., with a period of about 12 y in the case of Jupiter). The maximum eccentricity $e_{\max}$, imparted to an initially circular grain, is inversely proportional to its radius, and as a result, grains of radii less than a critical value, $R_{\min}$, will collide with the planet during a Jovian year, where

$$R_{\min} \simeq \frac{2.5 \times 10^{-5}}{\rho_g} \left[\frac{(2 - R_{J/a})^{1/2}}{(1 - R_{J/a})}\right], \tag{6}$$

a being the semi-major axes (Peale, 1966). With $\rho_g \simeq 2$ g cm^{-3} and $a \simeq 35R_J$, we get $R_{\min} \simeq 2 \times 10^{-5}$ cm. Consequently, grains larger than $0.2\,\mu$ will not be removed by collision with the planet during a Jovian year. But the orbits of even $1\,\mu$ sized grains will be significantly altered by this effect with a periodicity $\simeq 12$ y. This result is, of course, applicable only to uncharged grains which are initially moving in circular orbits. While this may also provide a rough estimate of the time scale of the radiation pressure induced variation of the more complicated charged dust orbits, it is clearly orders of magnitude larger than the electric field induced variation; the characteristic time for the completion of a single loop (see Figures 2–4) being typically only a few hours. Consequently, the fastest evolution of the charged dust orbits must still be associated with the electrodynamic effects we have discussed earlier.

5. Discussion

In Paper I, we claimed that the sudden increase by over one order of magnitude of the dust flux measured by the penetration experiment on Pioneer 10 at about $30R_J$ (Humes *et al.*, 1974, 1975) was the combined result of electrostatic disruption of fragile grains entering the outer edge of the Jovian plasma disc, and the subsequent magneto-gravitational trapping or focusing of these grains. At first glance, Figure 10 seems to indicate that the enhancement around the outer edge (in this case, $35R_J$) is not so large. This is, however, only because the dust density in the outer regions is 2 to 3 orders of magnitude smaller than those in the inner regions. No comparison is intended between the densities inside and outside the magnetosphere. It is, however, clear that the very processes of disruption of the larger grains around $35R_J$ must increase the density of smaller grains there. For instance, if the interplanetary dust distribution has a power spectrum with size index n ($\lesssim 4$), and cutoffs in the grain radius at $R_{\min}$ and $R_{\max}$ ($R_{\max} \gg R_{\min}$), then it is easy to show that the cumulative mass from the radius, $R_{\min}$, up to some value, R, is given by

$$M(R) = M\left[\left(\frac{R}{R_{\max}}\right)^{4-n} - \left(\frac{R_{\min}}{R_{\max}}\right)^{4-n}\right], \tag{7}$$

where M is the total mass from $R_{\min}$ to $R_{\max}$. If we take $R_{\min} = 0.3\,\mu$ it is seen that the mass in the decade ($3\,\mu$–$30\,\mu$), is about 3 times the mass in the decade ($0.3\,\mu$–$3\,\mu$), if $n = 3.5$, whereas it is about 10 times when $n = 3$. Also, the outer turning points in the orbits of all the recently captured grains is around $30R_J$, causing a peak there (see Figure 6). Furthermore, the speed of the grains are now around 6 to 7 times larger in this region than if they were uncharged. Consequently, a modest increase in the dust flux by an order of a magnitude or more at around $30R_J$ over the interplanetary value is to be expected.

It has been suggested that the Pioneer 10 observations of the dust enhancement near Jupiter may be accounted for purely on the basis of gravitational focusing by the planet (Humes *et al.*, 1974; Singer and Stanley, 1976). It is, however, difficult to understand why gravitational focusing would provide a sudden increase in the dust flux at around $30R_J$. The gravitational focusing mechanism should produce a more gradual increase and should be effective within the Laplacian sphere of influence of Jupiter, which has a radius $\Sigma_J = (M_J/M_\odot)^{2/5} r_J \simeq 660R_J$ (where r_J is the heliocentric distance of Jupiter). The variation in the relative density of interplanetary dust due to the gravitational focusing by the Earth has been evaluated by Colombo *et al.* (1966), where it is found to depend largely on the ratio (v_∞/v_e); v_e being the velocity of escape from the planetary surface, and v_∞ being the velocity of the dust grain relative to the planet at a large distance from it.

It was shown that when $v_\infty/v_e \gtrsim 0.1$ the relative density remains almost constant with no appreciable increase towards the planet. On the other hand, when $v_\infty/v_e \simeq 0.01$, there is a significant increase in the relative density, reaching a maximum $\simeq 100$ at about $1.5R_\oplus$. Similar results would apply to Jupiter. Taking v_∞ to be the relative velocity of the interplanetary grains when at a distance Σ_J from Jupiter, we find that $v_\infty \simeq 2\,\text{km s}^{-1}$, giving $v_\infty/v_e \simeq 0.03$. Then using the relative density curves of Colombo *et al.* (1966), we find a maximum increase by a factor of 2 to 3 at about $1.5R_J$. It should also be noted that if the grains in question are sufficiently small to be influenced by solar radiation pressure (i.e. $R_J \lesssim 10\,\mu$), their Keplerian speeds at a given heliocentric distance would be substantially different from that of the larger bodies. It can be easily shown that when radiation pressure is taken into account, the effective value of μ $(= GM_\odot)$ is given by

$$\mu_{\text{eff}} = \mu\left(1 - \frac{3L_\odot q}{16\pi c G M_\odot}\,\frac{1}{\rho_g R_g}\right). \tag{8}$$

Consequently, for $1\,\mu$ sized grains of density $2\,\text{g cm}^{-3}$, $\mu_{\text{eff}} \simeq 0.7\,\mu$; which, in turn, provides a contribution to v_∞ of about another $2\,\text{km s}^{-1}$. For such small grains, the purely gravitational focusing mechanism would be even less effective than for the larger grains that are negligibly influenced by radiation pressure. One argument against the magneto-gravitational focusing mechanism that we propose (which is only valid for dust grains with radii $\lesssim 4\,\mu$) is that the Pioneer 10 micrometeoroid penetration detector is not sensitive to grains of mass $\lesssim 2 \times 10^{-9}$ g (Humes *et al.*, 1974). This is, of course, valid only for uncharged grains moving in Kepler orbits. The charged grain fragments are strongly accelerated by the co-rotational electric field to speeds 6 or 7 times greater than the Kepler speeds. These fragments have densities roughly 2 to 4 times that of the parent aggregates. Since the laboratory calibration of the Pioneer 10 dust detector suggests an 'energy-like' detection threshold for the mass of the form $m \propto \rho^{-0.5}v^{-2.5}$, grain fragments with masses as low as 10^{-11} g are detectable. This corresponds to a grain radius threshold of only about $1\,\mu$ if the density is assumed to be around $2\,\text{g cm}^{-3}$. Furthermore, the typical size of the grains in the thin Jovian dust ring recently discovered by cameras aboard Voyager 1 at a Jovicentric distance $\simeq 1.8R_J$ (Smith *et al.*, 1979), may be only a few microns based on forward-scatter data (A. F. Cook, private communication, 1979).

With regard to the origin of the aforementioned dust ring, it is tempting to suggest that it may be associated with the magneto-gravitational capture and subsequent focusing of charged dust towards the synchronous orbit as discussed in Section 4. However, even if we allow for the inclination of the magnetic axis to the spin axis of the planet ($\simeq 10^\circ$), this amounts to over $2.1R_J$ rather than $1.8R_J$, which is a substantial discrepancy. On the other hand, all the perturbations we discussed at the end of Section 4 may prevent the strong focusing of this dust band to a thin ring around $2.2R_J$, and rather, produce a more diffuse band centered around that distance. We have examined whether there are any likely orbital resonances with the Jovian satellites which could produce the observed thin ring around $1.8R_J$. The only reasonable ones we can find (to $\lesssim 1\%$ accuracy) are a high order of 4:7 resonance with Amalthea (which is at $2.6R_J$) and a 1:6 resonance with Io (which is at $5.9R_J$). While Amalthea is very close to the ring, its extremely small mass compared with Jupiter ($M_A/M_J \lesssim 10^{-8}$) makes it an unlikely candidate to produce a significant gravitational effect on the ring. Nor is the 1 : 6 resonance with Io too convincing. However, the recently discovered small satellite just outside the ring at about $1.81R_J$ (Danielson and Jewitt, 1979) may interact with these spiraling grains to form the ring. So the question must remain open at this time. Our only contention at present is that the aforementioned dust belt centered around $2.2R_J$ may be the eventual source, directly or indirectly, of the observed dust ring around $1.8R_J$.

Since the actively volcanic satellite Io may also be a major source of dust within Jupiter, we have also investigated the possibility that it may alternatively be the source of the observed dust ring at $1.8R_J$. We find that grains of about $1\,\mu$ launched from Io (which is at $5.9R_J$), do not penetrate to less than about $4R_J$ in their first loop, as they get charged up by the plasma there. As the dust grain loses energy, it moves inward from around $5.9R_J$ to around $2R_J$ but much slower than the interplanetary grains. If the dust emitted by Io were so large that they are not sufficiently affected by the electromagnetic forces, then they will clearly distribute in a disc more or less centered around Io. The Poynting–Robertson effect discussed earlier will, of course, make the smaller grains spiral towards the planet. Making use of Equation (5), we see that the time taken for $1\,\mu$ sized grains to spiral from $2.1R_J$ to $1.8R_J$ is about 2×10^3 y, whereas the time taken by such grains to spiral in from $4R_J$ to $1.8R_J$ is over 10^5 y. (In this case too, the critical grain radius for removal by the Peale process in a single Jovian year $\simeq 0.22\,\mu$).

The near Earth flux of micrometeoroids ($m \lesssim 10^{-9}$ g) $\simeq 10^{-18}$ g cm^{-2} s^{-1} (e.g., Fechtig, 1976). If a similar flux near Jupiter is assumed, the rate of collection ($\dot{M}_D$) of micrometeoroids by a spherical belt of radius $35R_J$ and height $2R_J \simeq 2 \times 10^4$ g s^{-1} (since the magneto-gravitational capture efficiency $\simeq 1$, according to our computations). Therefore, in a steady state, the total mass M_D of the Jovian dust ring $\simeq \dot{M}_D \times \tau_l$, where τ_l is the characteristic loss time. If we take τ_l as the time taken for the $1\,\mu$ grains to spiral from $2R_J$ to $1R_J (\simeq 10^5$ y), $M_D \simeq 6 \times 10^{16}$ g. If, on the other hand, as we pointed out earlier, the loss time is much smaller (say only about 10^2 y), $M_D \simeq 6 \times 10^{13}$ g. Absorption by the Galilean satellites could reduce this value even further. Recently, Ip (1979) has estimated the mass of this dust ring on the basis of the observed absorption dip of the Jovian energetic particle data of Pioneer II. He gives a value of $M_D \simeq 5 \times 10^{14}\, d$ grams, where d is the average diameter of the grains in centimeters. If we take $d \simeq 2\,\mu$, $M_D \simeq 10^{11}$ g, whereas, if we take $d \simeq 2$ cm, $M_D \simeq 10^{15}$ g. Consequently, we have no difficulty in accounting for the mass of the dust ring by our mechanism of magneto-gravitational capture. If these grains sputter off secondaries from the newly discovered small satellite at $1.81R_J$, it would result in an additional source for M_D. Recently, Johnson *et al.* (1979) have estimated the Io resurfacing rate with the material in the Io volcanic plumes (which appear to be largely small dust grains). They claim a resurfacing rate $\simeq 3.5 \times 10^{-4}$ cm y^{-1}, which corresponds to about 10^6 g s^{-1}. Since the escape speed from Io $\simeq 2.5$ km s^{-1}, whereas the observed eruption speeds in the plumes $\lesssim 1$ km s^{-1}, assumption of a Maxwellian distribution of speeds imply a loss rate from Io of about

10^3 g s^{-1}. Consequently, the rate of supply of (volcanic) dust from Io to the Jovian dust belt appears to be over an order of magnitude less than that due to magneto-gravitational capture. However, due to the order of magnitude nature of the above calculations and the assumptions inherent in them, this comparison should be viewed with caution. In any case, we cannot exclude Io as an alternative source for the dust ring on the basis of its dust ejection rate, although the earlier discussion of the orbital evolution rates argues against it.

There are two other possibilities for the origin of the dust ring. One is that it is cosmogonic, consisting essentially of planetesimals which failed to agglomerate into a single body within the Roche limit of the planet. This seems unlikely, since the grains must have radii $\gtrsim 5$ cm in order for them to survive a cosmogonic time ($\simeq 5 \times 10^9$ y) without being lost via the Poynting–Robertson process, whereas they are likely to be typically only a few microns, as discussed earlier.

The other possibility is that the ring is of cometary origin. The Roche distance d_R for the tidal disruption of a body held together by its own gravitation, near Jupiter, is given by

$$d_R = \left(\frac{6M_J}{\pi\rho}\right)^{1/3}, \tag{9}$$

where ρ is the density of the body (e.g., Haymes, 1971). For a comet $\rho \simeq 1$ g cm^3 and, consequently, $d_R \simeq 2.2R_J$. On the other hand, the dominant force holding together a comet (whose radius is typically a few kilometers at most) is more likely to be its internal cohesion. In such a case, it is easily shown that the tidal disruption distance (d_T) is given by

$$d_T = \left(\frac{8GM_JR^2\rho}{3F}\right)^{1/3}, \tag{10}$$

where R is the radius of the body and F is its tensile strength. The tensile strength of comets (which, of course, could vary greatly from one to another) is imperfectly known. Sekanina (1977), on the basis of his calculations of the orbits of the fragments of Comet West (1975r) suggests a value for F as low as 10^3 dyne cm^{-2}. On the basis of the assumed similarity of the material in his 'icy congomerate' nucleus to that of terrestrial icicles, Whipple (1963) suggests larger values for F in the range 10^5–10^7 dyne cm^{-2}. In comparison with terrestrial dust balls and meteoroid material, Öpik (1956), on the other hand, suggests values of R in the 10^4–10^6 dyne cm^{-2}.

The variation of the tidal disruption distance with cometary radius for tensile strengths, F, varying between 10^3 dyne cm^{-2} to 10^6 dyne cm^{-2} is illustrated in Figure 12. It is seen that when F is small ($\simeq 10^3$ dyne cm^{-2}), the comet is tidally disrupted at the Roche distance ($\sim 2.2R_J$) for all values of the radius $R \gtrsim 1$ km. For values of R in the range (0.25 km $\lesssim R \lesssim 1$ km), the comet will be disrupted between the Roche distance and the planetary surface, whereas for values of $R \lesssim 0.25$ km, the comet will reach the planetary surface (or, more precisely, the lower levels of the atmosphere), before shock-induced

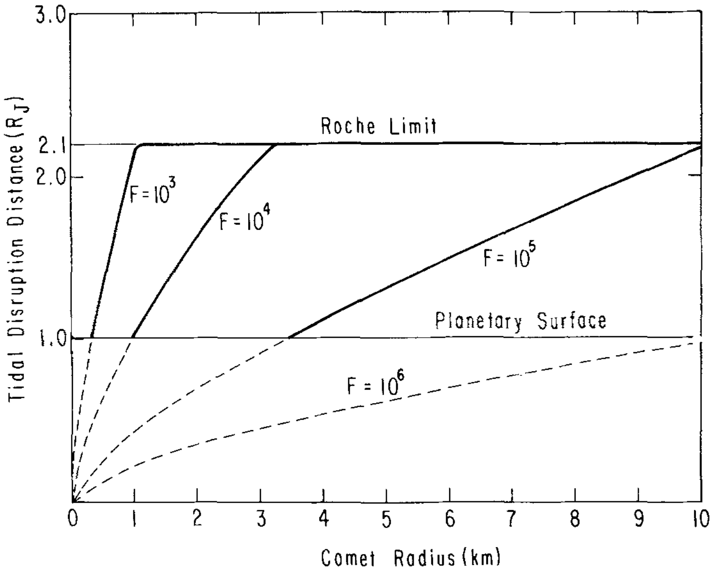

Fig. 12. Variation of the tidal disruption distance from radius of comets of various tensile strengths encountering Jupiter.

disintegration. On the other hand, when F is large ($\simeq 10^6$ dyne cm^{-2}), the comet will reach the planetary surface without disruption for $R \lesssim 10$ km.

Since cometary radii are typically in the range of about 1 to 3 km, it is clear from Figure 12 that they will reach the planetary surface without disruption if they are relatively strong (i.e., $F \gtrsim 10^5$ dyne cm^2). On the other hand, if they are very fragile (i.e., if $F \gtrsim 10^3$ dyne cm^2), they will disrupt at the Roche distance. In the intermediate group, 10^3 dyne cm^2 $\lesssim F \lesssim 10^4$ dyne cm^{-2}, the smaller comets will disrupt between the Roche distance and the planetary surface, whereas the larger ones will disrupt at the Roche distance.

If a comet were to be disrupted at, or below, the Roche distance (and, of course, above the planetary surface), the question arises as to what happens to its disruption fragments? If a comet moving in an essentially parabolic orbit around the Sun were to come within the Jovian sphere of influence, then in the Jovian frame of reference its velocity at a Jovicentric distance, r, is about $\sqrt{(v_J^2 + v_{es}^2)}$, where v_J is the heliocentric velocity of Jupiter, and v_{es} is the escape speed from Jupiter at the distance r. Consequently, the comet would be moving hyperbolically with respect to Jupiter. On tidal disruption, at or near the Roche limit, most of the fragments too will begin to move with essentially the same speed as the parent comet since the average extra velocity imparted to the fragments must be typically $\lesssim 1$ m s^{-1}, which corresponds to the velocity of escape from the cometary surface (only those fragments launched within a narrow angle about the retrograde direction with speeds $\gtrsim 1$ km s^{-1} can be gravitationally trapped by Jupiter.) Consequently, only a negligible mass of fragments would be gravitationally trapped by

Jupiter. Once again, the only plausible mechanism available for trapping of the fragments appears to be the magneto-gravitational one discussed in relation to the interplanetary grains entering the Jovian magnetosphere, and this would, of course, be effective only for micron-sized fragments which would acquire a high specific charge within the Jovian plasmasphere. Any such grain moving outwards from Jupiter will be strongly decelerated by the co-rotational electric field in the magnetosphere and if it is turned around before reaching the outer boundary of the plasmasphere at about $35R_J$, it would be stably trapped. The subsequent evolution of their orbits would, of course, be similar to those of the magneto-gravitationally captured interplanetary grains we have discussed earlier. There is, however, another problem associated with the sudden addition of so much material into the Jovian magnetosphere. If a comet of radius 1 km were to be broken up into essentially $1\,\mu$ sized grains, then eventual charging to -600 to -700 V will correspond to a total depletion of the entire Jovian plasmasphere inside the orbit of Io within the grain charge-up time of about 5 h. On the other hand, the time for refilling this region with ionospheric thermal plasma is almost one year (Mendis and Axford, 1974).

Finally, on the basis of the observational statistics of new comets, we estimate the frequency with which they come within $2R_J$ of Jupiter, is about one every 10^6 y whereas the frequency for short-period comets is about 10 times larger. Consequently, if the time scale for grain loss is much smaller than about 10^5 y, comet generated Jovian dust rings must be a transient phenomenon, with only a small probability of being observed at any given time.

All these lines of reasoning strengthen our conviction that the most likely source of the inner Jovian dust ring consists, either directly or indirectly, of magneto-gravitationally captured charged fragments of electrostatically disrupted interplanetary grains entering the Jovian magnetosphere.

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