VI

CIRCUMPLANETARY DUST

COLLISIONAL AND ELECTROSTATIC PROCESSES

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PHYSICAL PROCESSES ON CIRCUMPLANETARY DUST

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ABSTRACT. The life cycles of grains in circumplanetary space are governed by various physical processes that alter sizes and modify orbits. Lifetimes are quite short, perhaps 10^2-10^4 years for typical circumplanetary grains of 1 micron radius. Thus particles must be continually supplied to the circumplanetary complex, probably by the grinding down of larger parent bodies in collisions. Dust is eroded gradually through sublimation and through sputtering by the magnetospheric plasma but also is catastrophically destroyed through hypervelocity impacts with interplanetary micrometeoroids. Orbits evolve through momentum transfer (light drag, plasma or Coulomb drag, and atmospheric drag), and through resonant gravitational and electromagnetic forces. Plasma drag is generally the most effective evolution mechanism, with the possible exceptions of exospheric drag at Uranus and of electromagnetic schemes for some conditions. Since grains become charged (with typical electric potentials of a few volts), they undergo associated orbital perturbations: variable electromagnetic forces can cause the systematic drain of energy (orbital collapse) or, at specific (resonant) orbital locations can force large orbital inclinations/eccentricities. Solar radiation induces a periodic orbital eccentricity that can reach substantial values for 1 micron particles distant from the giant planets.

1. Introduction; The Circumplanetary Environment

Besides the interplanetary motes that are the subject of most articles in this book, dust is also found in faint ring systems about all of the giant planets (Burns *et al.* 1984, Ockert *et al.* 1987, Smith *et al.*1989, Esposito *et al.* 1991, Showalter *et al.* 1991, Showalter 1991) and exists at some level about the Earth and probably Mars (Soter 1971). Most of this material is located within several planetary radii of the parent planet concentrated near its equator. The typical circumplanetary particle has a size measured in microns. Even though the spatial density of circumplanetary dust is enormous compared to that of interplanetary grains, circumplanetary particles may still generally be considered to be isolated with mutual collisions being unimportant. The various physical processes that act on circumplanetary grains have been reviewed by Burns *et al.*(1979,1980, 1984), Grün (1984), Mendis *et al.* (1984), Mignard (1984), Schaffer (1989) and Goertz (1989).

These tenuous disks of material are of appreciable interest to planetary scientists for several reasons. First, they provide a testing ground for processes that may be obscured by the opacity of dense rings or that may be smoothed out by the frequent collisions occurring therein. Second, dust grains may regionally coat and color satellites embedded within the faint rings (cf. Cheng *et al.*1986). Third, the largest of the dust particles may prove hazardous to orbiting spacecraft such as Galileo and Cassini (Cuzzi *et al.* 1989, Burns *et al.* 1989).

A.C. Levasseur-Regourd and H. Hasegawa (eds.), Origin and Evolution of Interplanetary Dust, 341–348.

Lastly, circumplanetary particles exhibit interesting dynamical behavior.

The discussion below will first describe the environment in which these particles reside, then will consider the electrical charge that develops on the grains, will tabulate the magnitude of the accelerations suffered by the typical grain, will list how the circumplanetary complex might be supplied and lost, and finally will depict a few orbital histories of grains.

Circumplanetary dust is affected by the planet's gravitational and magnetic fields, and is continually bombarded by the local magnetospheric plasma. The planet's gravity dominates the orbital motion of micron-sized particles so that orbits are nearly Keplerian but, owing to various perturbing forces (some of which are described below), do undergo gradual evolution. The giant planets have crudely dipolar magnetic fields (Stevenson 1983), much like Earth's, although the fields of Uranus and Neptune are highly tilted and displaced from their planet's centers. Each magnetosphere is filled by a temporally and spatially variable plasma; the constitutive ions differ from system to system, with protons, oxygen and sulfur prominent at Jupiter, protons and oxygen dominant at Saturn, and protons predominant at Earth, Uranus and Neptune. Because the magnetospheric plasma is tied to the planet's rotating magnetic field and, due to its approximately infinite conductivity, cannot sustain an electric field in its *own reference frame*, a "corotational" electric field $\mathbf{E}=\Omega\mathbf{B}\mathbf{r}/c$ where Ω is the planet's angular spin rate, $\mathbf{r}$ is the radial vector to the particle, B is the local magnetic field and c is the speed of light) is present in *inertial* space (see Burns and Schaffer 1989). The electromagnetic and plasma environments for those planets with little or no intrinsic magnetic field are fixed by the solar wind's flow past the planet (see Horanyi *et al.* 1990).

Particles are also subject to the Sun's radiation, which produces a force (Burns *et al.* 1979, Mignard 1984) and affects the particle's charge, and to a continual rain of micrometeoroids, which can catastrophically shatter circumplanetary dust (Burns *et al.* 1980).

2. Electrical Charging

Surfaces in space build up electrical charges because they are bathed in a plasma and because they eject electrons through the solar photoelectric effect. Various schemes have been developed to compute the surface potential that will form under ambient conditions (Whipple 1981, Schaffer 1989). Typically the resultant potential is negative since, in the usual magnetospheric plasma, the temperatures of the electrons and the ions are nearly the same (owing to equipartition of energy), meaning that the electrons move much faster and are thus able to reach the surface first. The potential builds to the point where the current flow in ambient electrons and ions plus photo-ejected particles is zero. As a rough rule of thumb, a typical potential (expressed in volts) for an isolated particle in a hydrogen plasma is a factor of 2.5 times the plasma temperature (in electron volts); for a micron-sized grain, this corresponds to an excess charge N of several thousand electrons. Figure 1 gives some examples. Timescales for acquiring this charge depend on the composition and density of the local plasma as well as the grain's size since these properties determine the frequency at which charged particles strike the grain; for micron dust about the giant planets, charging timescales are tens of seconds to hours whereas orbits take tens of hours to complete.

The charge on any particular grain varies for several reasons. First the charging process is fundamentally stochastic because any plasma has a distribution of speeds and a charge's ability to gain access to the grain will depend on its speed. Typical variations are about $N^{1/2}/2$ (Schaffer 1989), a factor of two less than the usual statistical process because, once a grain's charge drifts away from the equilibrium value, that grain preferentially attracts charges of the appropriate sign so as to return toward equilibrium. Second, dust is likely to sample different plasma compositions, temperatures, and densities as the planet is orbited. Similarly, the plasma flow onto the grain depends partly on the dust's speed relative to the mean flow of

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the plasma (which approximately corotates with the planet's magnetic field) and the dust's speed varies systematically along any orbit but a circular equatorial one (Burns and Schaffer 1989, Northrop *et al.* 1989). Finally the particle's charge will be periodically modulated whenever the grain moves across the planet's shadow; this variation is only appreciable at Jupiter or closer to the Sun for elsewhere the total photoelectron current flow is negligible.

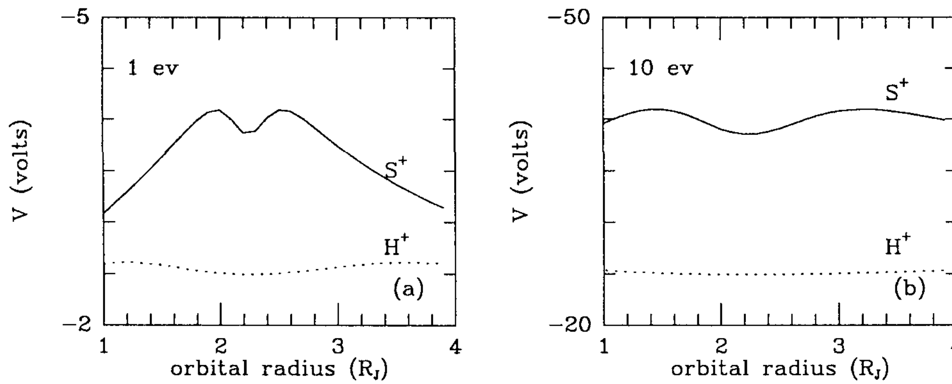

Figure 1. Equilibrium potentials vs. orbital radius in Jupiter's magnetosphere for two uniform density plasmas: a.) a S^+ or H^+ plasma with a temperature T of 1 ev; b.) T = 10 ev. The minima near the plots' centers occur at the synchronous orbit where Ω=n (from Schaffer 1989).

The above discussion assumes that the particles are isolated in space. O. Havnes, C. K. Goertz, G. E. Morfill, E. Whipple and their colleagues have addressed the circumstances under which a layer of dust might operate collectively to ward off the surrounding plasma or a planetary ring might develop vertical structure to support the electrostatic potential (Goertz 1989). For most tenuous planetary rings, with the unlikely exception of Uranus where a Coulomb lattice might develop, this complication of shielding is unimportant.

Electrical effects have also been invoked to modify particle sizes (see Burns *et al.* 1980, Mendis *et al.* 1984) and to produce Saturn's spokes (Grün *et al.* 1984, Goertz 1989).

3. Accelerations; Loss and Supply

Accelerations provide only a rough idea of the long-term significance of various forces since orbital evolution depends on the phasing of the perturbations (see, e.g., Burns 1976). Nevertheless in Table 1 we simply estimate the largest accelerations that act on 1 micron particles placed in the equatorial planes of the giant planets at r=1.8R, where R is the planetary radius. The acceleration due to planetary oblateness (J_2 being the gravity field's oblateness coefficient) is approximately $(3/2)J_2(R/r)^2$ *times* the local gravitational acceleration g. The solar radiation pressure acceleration is directed away from the Sun and is $(3SQ_{pr})/(4\rho csd^2)$, where S is the solar constant, Q_{pr} is the radiation pressure coefficient, ρ is the particle's density and s its radius, and d is the planet's distance from the Sun in AU (Burns *et al.* 1979). The Lorentz force felt by a charged grain moving relative to the planet's B field (assumed to be a dipole: $b_{1,0}R^3/r^3$) is $3\Phi(n-\Omega)b_{1,0}R^3/(4\pi\rho cGMs^2)$ *times* g, where n is the particle's orbital rate, Φ is the surface potential, G is the gravitational constant and M is the planet's mass (Schaffer and Burns 1987). Note that forces, such as drags, that depend on surface area πs^2 have accelerations varying as s^{-1} whereas electromagnetic accelerations differ

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as s^{-2} since surface potentials are generally constant for a specific plasma. This of course means that nongravitational accelerations, especially electromagnetic ones, become more important on small particles. The tabulated numbers for dust in the rings of Jupiter and Saturn come from Burns *et al.* (1984) while those of Uranus are taken from Esposito *et al.* (1991).

TABLE 1. Orbital Accelerations and Life/Death Processes for 1 μm Dust at 1.8 R

Accelerations (in cm/sec^2)	**Jupiter**	**Saturn**	**Uranus**	**Neptune**
Gravity ($\sim r^{-2}$)	800	350	275	350
Oblateness ($\sim r^{-4}$)	5	3	0.5	0.6
Radiation Pressure ($\sim s^{-1}$)	0.1	0.03	0.01	0.003
Electromagnetic ($\sim s^{-2}$)	1	0.05	0.03	0.02
Lifetimes (in years)	**Jupiter**	**Saturn**	**Uranus**	**Neptune**
Orbital Evolution				
Poynting-Robertson ($\sim s$)	10^5	$\leq 10^6$	10^6	10^6–10^7
Plasma Drag($\sim s$)	$2 \times 10^{2\pm1}$	$10^{5\pm1}$	$10^{5\pm1}$	$10^{6\pm2}$
Exospheric Drag ($\sim s r^{3/2} e^{-3r/r}$)	—	—	$10^{2\pm1}$	10^5–10^6
Electromagnetic Variations ($\sim s^2 r^?$)	?	?	?	?
Erosion				
Sublimation ($\sim s$)	10^7	10^{17}	$\ll\infty$	$<\infty$
Sputtering ($\sim s$)	$10^{3\pm1}$	$10^{3\pm1}$	$10^{5\pm2}$	$10^{7\pm2}$
Micrometeoroid Shattering($\sim s^{-2}$)	$10^{5\pm1}$	$10^{6\pm1}$	$10^{6\pm2}$	$10^{6\pm2}$

Many processes act to eliminate small grains. Orbits evolve via radiation drag, plasma drag, atmospheric drag and electromagnetic effects; meanwhile tiny grains may be destroyed—but also be born—in catastrophic collisions, or may sublimate or sputter away. Fine debris may be sloughed off moonlets in mutual collisions (Cuzzi and Burns 1988, Colwell and Esposito 1990) or following energetic impacts by interplanetary meteoroids (Burns *et al.* 1980)—but debris may also reaccumulate on such parents and may thereby be temporarily lost from the complex. Minute grains may be launched by volcanoes or geysers onto circumplanetary orbits similar to that of the satellite. Particles may also condense directly from the local gas. Burns *et al.* (1984), Grün *et al.* (1984) and Esposito *et al.* (1991) summarize many of these processes and provide the timescales listed in Table 1.

4. Orbital Histories

The long-term orbital evolution of circumplanetary dust grains under various combinations of the perturbations described above has been an active research subject over the last few years. Most papers have merely demonstrated the efficacy of particular mechanisms for evolving dust. Here, because of limited space, we will restrict ourselves to simply showing the nature of some of the mechanisms; the original papers should be consulted for details of the calculations. As yet, no comprehensive treatment of these processes is available; nevertheless it is clear that such processes are important in transporting circumplanetary grains.

Most of these mechanisms rely on resonant forces; such periodic forces can produce long-term consequences if they are accompanied by a phase delay. Periodic Lorentz forces occur owing to motion through a spatially variable magnetic field (Fig. 2) or a periodic charge (Figs. 4 and 6). Since elliptical orbits always precess (e.g., due to J_2), any evolutions that rely on orbital alignment always are temporary (Figs. 5 and 6).

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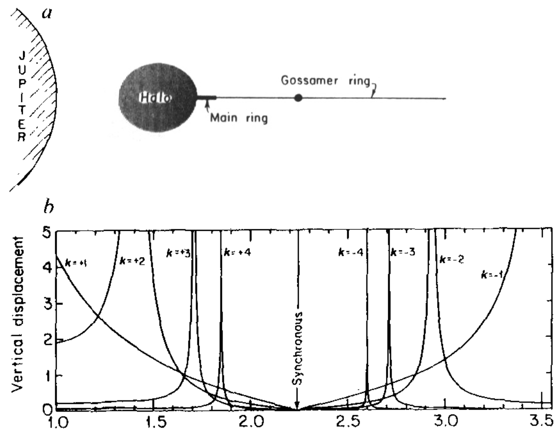

Figure 2. Jovian ring boundaries, plotted vs. planetary radii, are compared with positions of some low-order Lorentz resonances (LR). LR occur wherever the particle's orbital rate n is commensurate with the rate $k(\Omega - n)$at which the k^{th} component of the planet's magnetic field is traversed; LR peak at a doubly infinite set of planetary radii. At these positions the Lorentz force, which in general has both vertical and horizontal components, contains a frequency that resonates with n. Vertical responses to low-order Lorentz force components across the ring region are shown in arbitrary units. Jupiter's vertically extended halo appears to be confined by the k=2 and the k=3 LR (Burns *et al.* 1985).

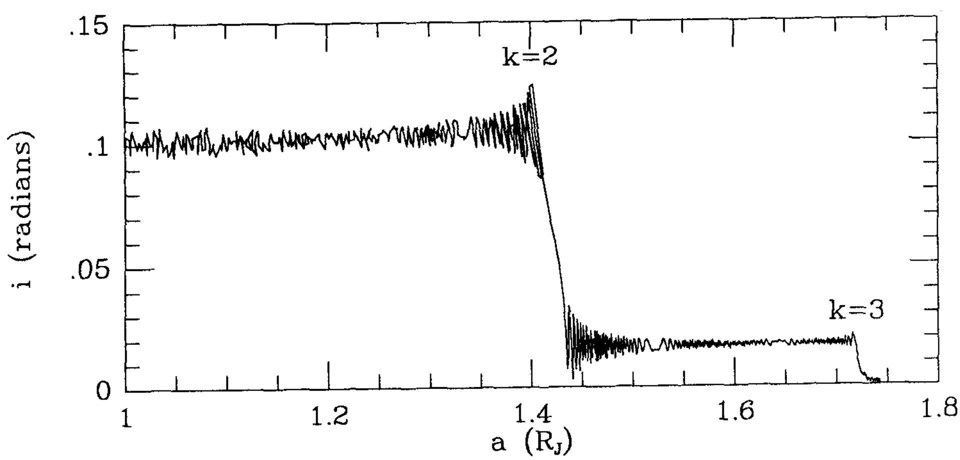

Figure 3. Passage through the k=3 and k=2 inner LR of Jupiter for a 1 μm, −1 volt grain that drifts inward radially at rate $\dot{a} \approx -0.2$ m/sec. As shown here, when particles move through Lorentz resonances, their inclinations (and eccentricities) undergo large jumps which persist after resonance passage if passage does not occur too rapidly. Dust from Jupiter's main ring may thus cause the halo. Similar phenomena occur at gravitational resonances. (From Schaffer 1989).

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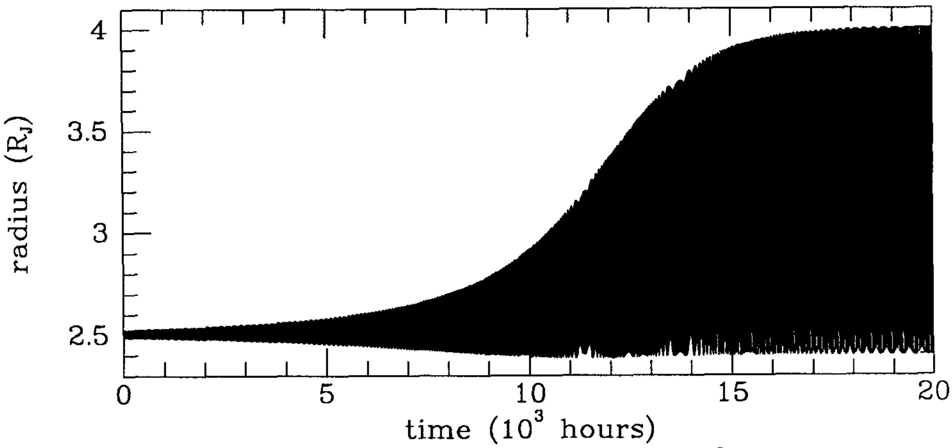

Figure 4. The evolution of a grain due to *resonant charge variation.* Grains that move along elliptical orbits experience charge variations that, if properly timed, can cause work to be done by (or to) the corotational electric field when integrated over a complete orbit; this work occurs because of a time delay in the grain's charging and is ultimately drawn from the orbit's energy (Burns 1976). For this plot, the grain was launched on a circular equatorial path at 2.54 R_J but, because of the electric charge it developed, its orbit quickly becomes elliptic, allowing this orbital evolution mechanism to proceed. (From Burns and Schaffer 1989).

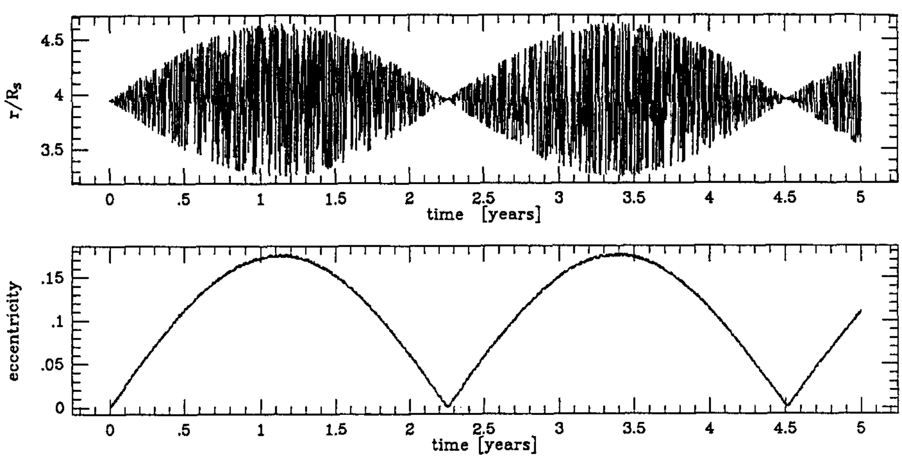

Figure 5. The effect of *solar radiation pressure.* Circumplanetary particles that start on prograde circular paths immediately develop an increasingly elongated orbit, initially pointing in the direction of the planet's orbital motion about the Sun. However, since the eccentricity growth per orbital period depends on the orientation of the elongated orbit relative to the solar force and since elliptical orbits precess (at roughly a constant rate) due to either the planet's oblateness, the corotational electric field or the planet's orbital motion about the Sun, the eccentricity growth will eventually be halted as the particle's orbital line of apses passes through the line directed toward the Sun. After this point the orbit's eccentricity gradually decreases until the orbit becomes circular once again at which time the cycle repeats. (From Burns and Horanyi 1990). Since energy is conserved, the orbit size does not change.

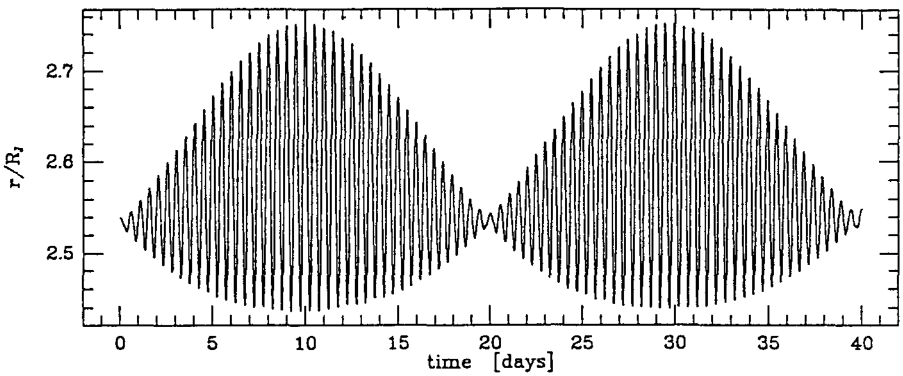

Figure 6. The evolution of a 1μm particle's orbit owing to *passage through Jupiter's shadow,* including solar radiation pressure. The latter force starts to drive an eccentricity oscillation as in Fig. 5. However shadow passage causes the charge to vary with the orbit period and thereby produces a force resonant with the orbit. The orbit precesses due to the planet's oblateness. The orbit's mean size is seen to vary with a twenty day period; the work done on the particle is non-zero over the orbit period because the charge on the grain when the particle is in the planet's shadow differs from that at similar orbital radii when in sunlight. The re-orientation ultimately changes the sign of the work done so that large orbital variations do not occur. (From Horanyi and Burns 1991).

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