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Gravito-electrodynamics and the structure of planetary ring systems

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Abstract. Recent spacecraft observations of the Saturnian and Jovian ring systems have highlighted a plethora of interesting new phenomena associated with those regions containing fine (micron and sub-micron sized) dust. Recognizing that these dust grains, by virtue of being immersed within the planetary magnetospheres, are electrostatically charged to the point that they experience comparable gravitational and electric forces, a new "gravito-electrodynamic" theory has been developed to describe their dynamics. This theory has been successful in explaining all these phenomena in a systematic way. In this review, the basic model and its range of validity are outlined, and its application to the Saturnian and Jovian ring systems are discussed.

Keywords. Gravito-electrodynamic; structure of planetary ring system; Saturnian ring system; Jovian ring system.

1. Introduction

Particulate matter in the solar system, whether it be within planetary magnetospheres or in interplanetary space is immersed in a radiative and plasma environment. As a result this material is electrostatically charged to some finite electric potential, which may be positive or negative depending largely on the relative strengths of photo-emission and the electron collection currents of the body. While this charging has only physical effects, such as electrostatic 'chipping' and disruption, on the larger bodies (*e.g.* see Mendis 1981), it can also effect the dynamics of the smaller grains.

Of particular interest are the fine (micron and sub-micron sized) dust particles that have been observed in both the Jovian and Saturnian magnetospheres by the recent Pioneer and Voyager spacecrafts. While the entire diffuse Jovian dust-disc, extending inwards for about 30 R_J together with its contiguous thin ring around 1·8 R_J, seem to be composed of such fine dust, so do many regions of the Saturnian ring system (*e.g.* the *D*, *E*, *F* and *G* rings, the radial "spokes," and some eccentric ringlets).

While the larger bodies within planetary magnetospheres (*e.g.* satellites, boulders, etc.) are overwhelmingly influenced by gravitational forces, the electrons and ions are overwhelmingly influenced by electromagnetic forces, with planetary gravity playing only a very secondary role (*e.g.* causing slow azimuthal drifts). While Newtonian mechanics describe the motion of the former, electrodynamics describe the motion of the latter. In micron and sub-micron sized particles in these planetary magnetospheres, however, the gravitational and electromagnetic forces they experience can become comparable, at least to within an order of magnitude. In that case neither Newtonian mechanics nor electrodynamics is adequate for studying the motion of such grains; what is required is a combination of the two—namely 'gravito-electrodynamics'.

Such a theory has recently been developed specifically to explain a number of interesting phenomena observed in the Saturnian and Jovian ring systems (Mendis *et al*

1982, 1983a). Here we will give a rather short review of the basic theory and its applications to the planetary ring systems. More comprehensive reviews of its application to planetary rings in general and Saturn's ring system in particular are given in Grun *et al* (1983) and Mendis *et al* (1983b) respectively.

2. The basic model and its range of validity

The equation of motion of a charged dust grain in the planet-centered inertial frame is given, with the usual notation, by

$$\ddot{\mathbf{r}} = \frac{q(t)}{m}\left(E + \frac{\dot{\mathbf{r}}}{c} \times \mathbf{B}\right) - \frac{GM_p}{r^3}\mathbf{r} + \mathbf{F}, \tag{1}$$

where $\mathbf{F}$ represents forces associated with collisions with photons, plasma and other grains.

Within the rigidly co-rotating regions of the planetary magnetosphere, where the ring systems are observed

$$\mathbf{E} = -\frac{1}{c}(\mathbf{\Omega}_p \times \mathbf{r}) \times \mathbf{B}, \tag{2}$$

where $\mathbf{\Omega}_p$ is the angular velocity of the planet. This is, of course, strictly applicable only when the Debye spheres of neighbouring grains do not intersect, otherwise the electric fields of neighbouring particles will also have to be included in $\mathbf{E}$. Also in this case, it has been suggested, that the surface charge that can be acquired by individual grains would be decreased (*e.g.* Grun 1982), as in a small grain lying on a large surface.

The condition of non-intersection of the Debye spheres is met in the diffuse dust disc of Jupiter and in the D and E rings of Saturn. It is barely met in the G ring of Saturn and the thin inner ring of Jupiter. In the other regions of the ring systems, where small grains are observed, namely in the F-ring and in the radial spokes of Saturn, this condition is not met. A recent analysis, wherein the Poisson equation in a dusty plasma has been solved with the appropriate boundary conditions (Whipple *et al* 1983) has, however, shown that while the capacitance of a grain, surrounded by other grains and plasma, increases rather than decreases (as suggested by Grun 1982), its value in the F-ring and the spokes would vary from its free-space value by less than 1 %. Also it is easy to see that the co-rotation E-field due to the polarization of the plasma dominates over the E-fields of neighbouring grains, even when the Debye spheres overlap. In other words while the gravito-electrodynamic theory strictly applies only when the Debye spheres of neighbouring grains do not intersect, it is a very good approximation even when they do, in the many cases of interest.

If the magnetic moment and the spin vector are strictly parallel (which is true in the Saturnian case, and is a fair approximation in the Jovian case) and if $\mathbf{F} = \mathbf{0}$ (as is true in both ring systems), it is easy to show that (1) and (2) admit circular orbits in the equatorial plane, moving with angular velocity, Ω_G, given by,

$$\Omega_G = \frac{\omega_0}{2}[-1 \pm (1 + 4(\Omega_p/\omega_0) + (\Omega_K^2/\omega_0^2))^{1/2}] \tag{3}$$

where Ω_K is the local Kepler velocity and ω_0 is given by

$$\omega_0 = -(qB/mc). \tag{4}$$

Equation (4) shows that two different motions are possible for a given grain. The plus sign in front of the radical corresponds to direct (or prograde) motion, while the negative sign corresponds to indirect (or retrograde) motion, for a negatively charged grain. For a positively charged grain, the minus sign in front of the radical gives a prograde motion, while the plus sign gives a prograde or retrograde motion depending on the value of ω_0.

If χ ($= |F_E/F_G|$) is the ratio of the electric force to the gravitational force on grains in circular orbits, in the inertial frame, then using (1) we get

$$\chi = \frac{|\Omega_G - \Omega_p|\,\omega_0 L^3 R_p^3}{GM_p}, \tag{5}$$

where $L = r/R_p$. The χ values for negatively charged grains, having different sizes and electrostatic potentials, at different positions in the Saturnian ring system have been calculated by Mendis *et al* (1983) using (5). This is shown in figure 1. It is clear that electromagnetic forces are important for micron and sub-micron sized grains for any reasonable ϕ value. Any attempt to bracket the range of χ for application of gravitoelectro-dynamics is necessarily arbitrary, but the range of $\chi \gtrsim 10^{-2}$ may be reasonable. It must be noted that even when $\chi \approx 10^{-2}$, the electric force on the grain is many orders of magnitude larger than, for instance, the typical gravitational perturbing force of a nearby satellite. Therefore, in this case, while the grain orbit is largely controlled by gravitation, the perturbation produced by electromagnetic forces is sufficient to give rise to various subtle effects that are observed.

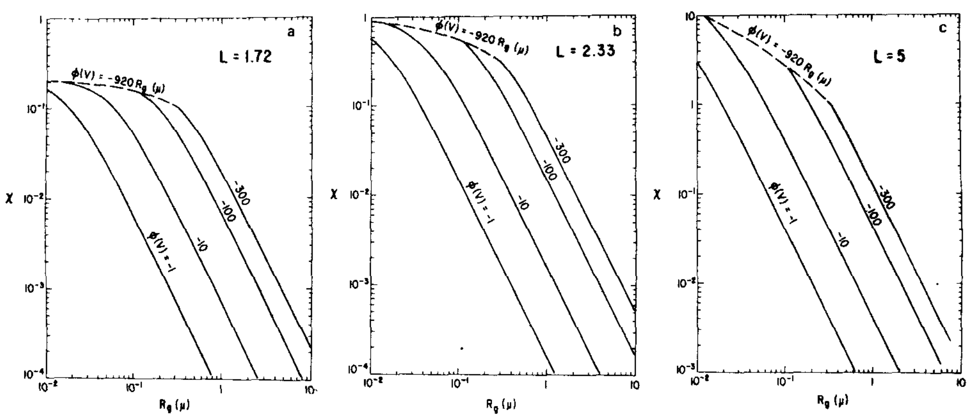

Figure 1. The variation of χ (the ratio of the electric to the gravitational force) on grains of different sizes and different potentials at various positions within the Saturnian magnetospheres. (a) corresponds to L ($= r/R_k$) $= 1{\cdot}72$, which is the inner boundary of the "spokes," (b) corresponds to $L = 2{\cdot}33$, which is the centre of the F-ring, and (c) corresponds to $L = 5$ a position within the broad E-ring (from Mendis *et al* 1983).

3. Nature and stability of charged dust orbits

Let us next consider the basic nature and the stability of the charged grain orbits within a planetary magnetosphere. If a charged dust grain, moving in a circular orbit in the equatorial plane of the planet (whose magnetic moment and spin are assumed to be strictly parallel) is subject to a small perturbation in the plane (*e.g.* by the gravitational tug of a nearby satellite) it has been shown (Mendis *et al* 1982) that the grain will perform a motion that can be described as an elliptical gyration about a guiding centre which is moving with an angular velocity Ω_G (equation (3)). The gyration frequency, ω, about the guiding centre is given by

$$\omega^2 = \omega_0^2 + 4\omega_0 \Omega_G + \Omega_G^2. \tag{6}$$

Also, if a and b are the semi-major and semi-minor axes of this ellipse, it is shown that

$$\frac{b}{a} = -\frac{\omega}{2\Omega_G + \omega_0} \tag{7}$$

with the minor axis aligned in the radial direction.

Not all the grains are radially stable. Those that are, must satisfy the condition $\omega^2 > 0$. This has been used by Mendis *et al* (1982) to obtain the stable orbits at any given distance from the planet. The classes of stable and unstable orbits within the rigidly co-rotating portion of the Saturnian magnetosphere are exhibited in general

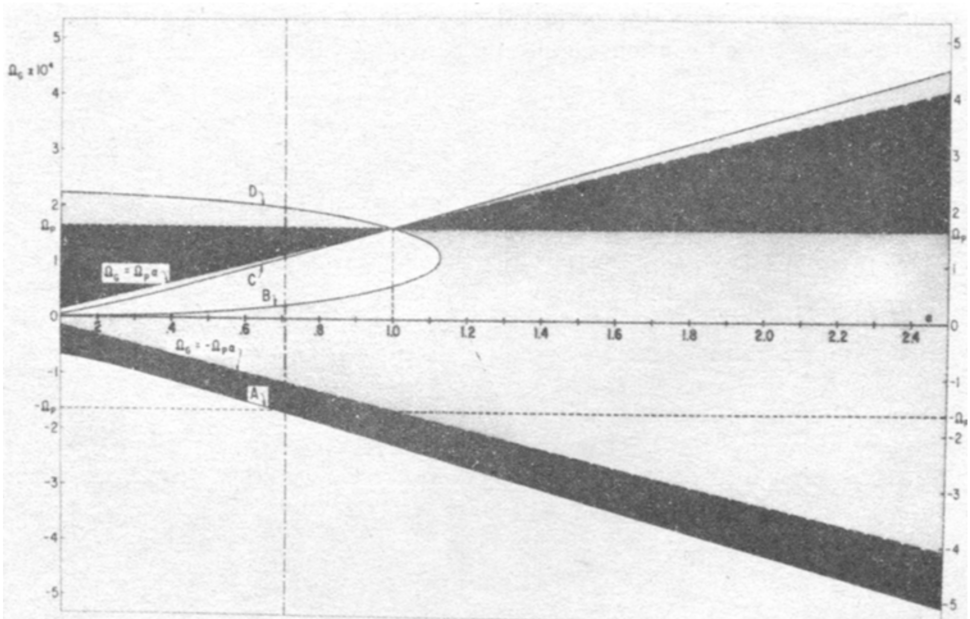

Figure 2. The variation of Ω_G with α ($= \Omega_K/\Omega_p$, with $\Omega_p = \Omega_h$ in the case of Saturn). The curves marked A, B, C, D indicate the Ω_G values when $\omega^2 = 0$, for various α values. The shaded regions are where $\omega^2 > 0$ and the unshaded regions are where $\omega^2 < 0$. The dark and light shading correspond to negative and positive particles respectively. The lines marked $\Omega_G = \pm\Omega_p\alpha$ represent Kepler particles, while the dashed line marked $\Omega_G = \Omega_p$ represents the co-rotating particles. The values of $\alpha = 0{\cdot}1, 0{\cdot}7, 1$, and $2{\cdot}5$ correspond respectively to $10\ R_h$, the *F*-ring, the synchronous orbit, and Saturn's surface (From Mendis *et al* 1982).

(figure 2). Here $\alpha = (\Omega_K/\Omega_p)$ is the independent variable and Ω_G is the dependent variable.

It is seen, for instance, that at the distance of the F-ring, negative particles of all sizes, from the smallest (co-rotating) to the largest (essentially Keplerian) particles moving in the prograde sense are stably trapped. Interestingly, it is seen that there are several other distributions of particles that are also stably trapped there. This figure has been used by Hill and Mendis (1982a) to fix the polarity of the grains that compose the B-ring spokes. This point will be discussed later.

Northrop and Hill (1982, 1983a) have also studied the stability of negatively charged grains in the equatorial plane of Saturn subject to perturbations normal to the ring plane. They find that there exists a critical radius, which depends on the specific charge on the grain, such that grains interior to that are unstable to normal perturbations. They have used this fact to discuss the existence of a sharp boundary between the inner and outer parts of Saturn's B-ring as well as the inner edge of the B-ring.

4. Magneto-gravitational resonance and F-ring waves

From figure 2 it is seen that negatively charged grains in the F-ring are moving with an angular velocity Ω_G which is larger than the Kepler angular velocity at their distance. Since Ω_G depends on ω_0 and therefore on the grain size R_g for a given potential, there would be grains of a certain size which would move with the same angular speed Ω_s of a satellite interior to the grain orbit (as long as $\Omega_K < \Omega_s < \Omega_h$). This means an exact 1 : 1 orbit-orbit resonance with such a satellite. A similar situation clearly does not arise with pure gravitational resonances. This has been named a *magneto-gravitational resonance*.

The condition $\Omega_G = \Omega_s$ for the magneto-gravitational resonance, gives a critical value ω_{0c} for ω_0. This, in turn, gives the critical grain radius R_{gc}, for a given grain potential and density.

There are two newly discovered satellites S26 and S27 on either side of the F-ring, each within only about 1000 km of it. Of these, S27 is the inner one, being at a planetocentric distance of 2·31 R_h. This gives $R_{gc} \simeq 0{\cdot}5\ \mu$. Grains of this size in the F-ring will be strongly affected by S27.

It must be stressed here that, unlike a pure gravitational resonance, which affects particles of all sizes equally, the magneto-gravitational resonance picks out a particular grain size R_{gc}. Of course, grains with sizes close to R_{gc} (on either side of it) will also be strongly affected because their angular velocities will be close to that of the perturbing satellite, and will therefore remain in the vicinity of that satellite for long periods of time. If we consider such a particle with a gyration frequency ω about a guiding centre moving with angular velocity Ω_G, it can be shown that the grain will move in an undulating orbit having a wavelength λ given by

$$\lambda = \frac{2\pi r_f}{\omega}(\Omega_G - \Omega_s). \tag{8}$$

Furthermore, as each successive grain of the same size in the ring moves over the satellite it will be subject to the same perturbation and will therefore follow the same path as its predecessor in the frame of the satellite. Consequently, all the grains will move in phase to form a wavy pattern with the wavelength λ in the frame of the perturbing satellite. It has been proposed that the waves observed in the F-ring are formed this way (Mendis *et al* 1982). Substituting for Ω_G from (3) in (8) gives a dispersion relation between λ and ω, from which λ may be expressed as a function of R_g for a given ϕ value. Using an electron energy $kT_e \approx 10$ eV and electron density $n_e \approx 10^2$ cm^{-3}, Mendis *et al* (1982) find $\phi \approx -38$ V. Then the observed wavelength of $\lambda \approx 5000$ km in the F-ring corresponds to a grain size of about 0·45 μ. This corresponds very closely to the grain size determined by the light scattering phase function of the F-ring. The reason why a single wavelength is observed is presumably due to the fact that the size distribution is strongly peaked.

5. Gyro-orbital resonances and the eccentricity of the isolated ringlets

As a grain moves in from the sunlit side of Saturn to the shadow, its potential becomes more negative due to cut-off of the photo-emission from the grain. Consequently, the grain potential is modulated with a periodicity equal to its orbital period. It is found that if this period corresponds to the gyro-period of a grain of given size for a given potential, then a new type of "gyro-orbital resonance" is set up which strongly affects the grains' orbit. While this resonance will eventually remove the grains of this specific size, it will also strongly affect grains whose sizes are close to this critical size and in particular make their orbits deviate from circularity.

There are a number of narrow ringlets which are located within relatively broad regions of the Saturnian ring system, that are otherwise highly transparent. They also have two common properties; they are eccentric and they appear to be composed of fine dust ($R_g \approx 0{\cdot}5\ \mu$).

As a consequence of being in these highly transparent regions, where the magnetosphere plasma density is presumably relatively high, these grains are likely to be charged to significant negative potentials. Hill and Mendis (1982b) have calculated the orbits of grains of radius $R_g \approx 0{\cdot}5\ \mu$ in these regions and have shown that a near gyro-orbital resonance can cause the observed eccentricities. They also find that the eccentricity should increase with the distance of the ringlet from the synchronous orbit, a trend which is actually observed.

6. Electrostatic "blow-off" and the formation and evolution of the "spokes"

Among the most interesting features of the Saturnian ring system, first discovered by Voyager I and subsequently confirmed by Voyager 2 are the near-radial "spokes." Most of these spokes are confined to the dense central B-ring, which has its inner edge at 1·52 R_h and its outer edge at 1·95 R_h. The spokes themselves have their inner boundary at about 1·72 R_h and their outer boundary a. approximately the outer edge of the B-ring. Against the background of the B-ring they appear dark in back-scattered light and bright in forward scattered light, indicating that they are composed of small (micron and sub-micron) grains. The spokes exhibit a characteristic wedge shape with the vertex of the wedge coinciding with the position of the synchronous orbit at about 1·86 R_h.

Movies have been made to show the formation and dynamical evolution of these spokes. The spokes are more easily seen and seem to be more sharply defined on the morning ansa as they are rotated out of Saturn's shadow. While some of them appear to have been formed within the shadow, not all of them are. In fact, a new spoke was clearly seen to form in the middle of an existing pattern on the sunlit side. The time scale for formation of this spoke appears to be as short as 5 min.

The spoke motion has been measured by comparing the image of the rings taken tens of minute apart. The high resolution images of Voyager 2 show that the leading and trailing edges of a spoke have distinctly different angular velocities. Inside the synchronous orbit (where the spokes are mostly seen) the leading edge, which is tilted to the radial direction, has essentially a Keplerian rate, while the trailing edge, which is more or less radial, has approximately the co-rotational rate. Also, based on the observing geometry and the observed morphology of the spokes, Smith *et al* (1982) have argued that the material constituting the spokes is elevated above the ring plane.

Hill and Mendis (1981a) proposed that these small grains are charged and electrostatically levitated and blown off larger bodies (perhaps meter-sized) in the ring plane. The same proposal has also been made by a number of other authors (*e.g.* Goertz and Morfill 1983).

While Hill and Mendis (1981a) had earlier assumed that the charge was negative, they have since shown that the observed morphology of the spokes requires that the grains are indeed negatively charged. They have also discussed the detailed evolution of the fine dust grains constituting the spokes, once they are electrostatically blown off the surfaces of their parent bodies. They have numerically calculated the orbits of different sized grains as they move around the planet. What they find is that the so-called wedge is more like a ladies' fan, with several "ribs" (each corresponding to a region of enhanced grain density) all intersecting at a point on the synchronous orbit. The time evolution of the wedge would, according to this picture, constitute an opening of the fan, starting from its "closed" position corresponding to the radial (co-rotating) edge, and progressively unfolding in the direction of the slant (Kepler) edge. In fact, the analogy goes further, because the number of "ribs" exposed is shown to increase with time.

The most important conclusion of this picture of the evolution of the 'radial spokes' of Saturn is that their measured velocities (which the authors believe are the velocities of these aforementioned ribs of enhanced grain density) do not correspond to individual grain velocities as is generally believed (*e.g.* Smith *et al* 1982) but rather to *a phase velocity of a wave*. Each "rib" corresponds to a wave-front connecting grains, projected at different radial distances, but at the same phase of their motion.

This model also anticipates that the leading edge of this fan (inside the synchronous orbit) moves with an angular velocity slightly faster than the Keplerian one. Although the angular velocities calculated from Voyager 1 data do indeed show such super-Kepler angular velocities within the synchronous orbit, they all fall within the expected error bars. Therefore, at the present time the observation cannot be used to discriminate between the two interpretations of the measured velocities. What needs to be stressed, however, is that charged grains must necessarily move slower than Kepler velocities within the synchronous orbit, and if the super-Kepler angular velocities are indeed real, the only possible interpretation is as that of a wave, rather than of individual particles.

A somewhat different scenario, which however also invokes electrodynamic effects for the formation of the spokes has been proposed by Goertz and Morfill (1983) (see also Mendis *et al* 1983 for a more comprehensive review of this phenomenon).

7. Magneto-gravitational capture and the dust distribution in the Jovian magnetosphere

While the basic nature of magneto-gravitational orbits of charged dust grains in planetary magnetospheres was worked out by Mendis and Axford (1974), in order to explain the observed leading-trailing side asymmetries of Jovian and Saturnian satellites (see also, Wolff and Mendis 1983), detailed orbits were first computed by Hill and Mendis (1979, 1980, 1981) to study the micrometeoroid distribution within the Jovian magnetosphere. This work was motivated by the fact that the distribution of micrometeoroid dust observed within the Jovian magnetosphere by Pioneer 10 spacecraft could not be explained as due to gravitational focusing. In fact, the sudden increase of the micrometeoroid flux at about 35 R_J corresponded rather closely to the average distance of the plasma-pause. These authors postulated that fragile interplanetary micrometeoroids, on penetrating the Jovian plasmapause ($\sim 35\,R_J$) get rapidly charged to high electrostatic potentials (~ -100 V). These grains, or their electrostatic disruption products, have their initial purely gravitational orbits strongly modified by the electric forces within the co-rotating magnetosphere. One of the most important findings of this study was the following: since the grain surface potential is modulated by the relative speed between the grain and the plasma, and since the finite charging and discharging times of the grain introduced a phase lag in the potential with respect to the orbital position of the grain, it led to a "magneto-gravitational" trapping of these negatively charged grains within the magnetosphere, as illustrated in figure 3.

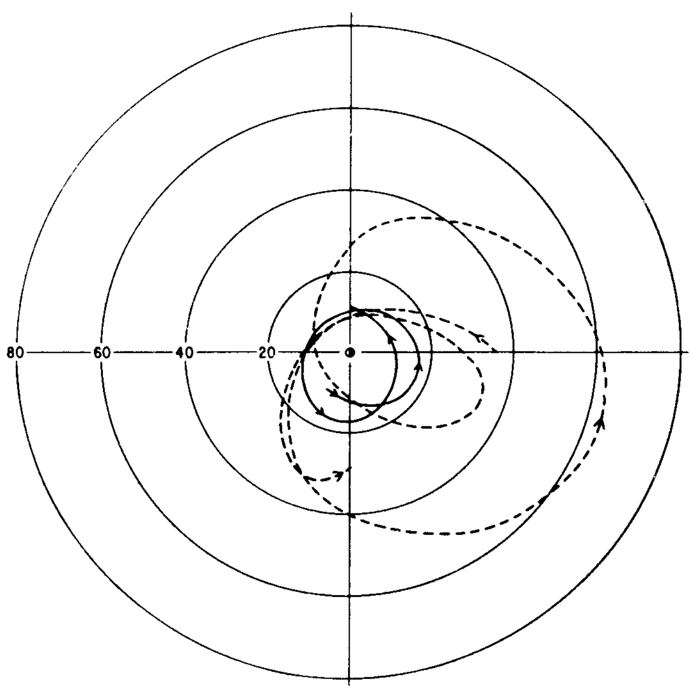

Figure 3. Orbit, in the inertial frame, of a 1·5 μ grain injected at the escape speed into the Jovian magnetosphere at 35 R_J, directed 45° inward from the prograde direction. The dotted curve represents the first few loops of the orbit, while the solid line represents the orbit after 200 days of evolution (From Hill and Mendis 1981).

A numerical simulation of the evolving spatial distribution of these grains in the equatorial plane (Hill and Mendis 1980) showed that the grain orbits evolve towards the synchronous orbit and get circularized at the same time. While the build-up of grains near the synchronous orbit approximately corresponded to the newly discovered inner Jovian ring around 1·8 R_J, the situation was complicated by the discovery of a small satellite around 1·81 R_J (Jewitt *et al* 1979) which could act as a secondary source of small dust grains, when impacted by the incoming primary micrometeoroid source.

In the numerical simulations, it was observed that as the evolving orbits became more circular the oscillation of the surface potential became smaller and the consequent orbital evolution became slower. This continuous slowing down caused much computing time, but the problem was overcome by the derivation of the adiabatic equations of motion of these dust grains by Northrop and Hill (1983b). This theory is an extension of the usual adiabatic theory of charged particle motion to include the complications of the variable grain charge. This analysis confirmed the earlier numerical analysis of Hill and Mendis (1980) but it showed that while the grain orbits evolve towards the synchronous orbit, they do so only as long as the magnetic moment of the grain is non-zero. Consequently, if the grain orbit was circularized before reaching the synchronous orbit, it would stop evolving at that distance. Since the radial drift (besides the usual azimuthal drift of the guiding centre in the adiabatic analysis) is caused by the phase lag of the grain potential with respect to its gyration, due to its finite capacitance, it has been named the *gyro-phase drift*.

8. Dust ring currents and their consequences

It was pointed out earlier that the charged dust in the ring moves with a speed that is different from the charge neutralizing surrounding plasma, which is assumed to be in rigid co-rotation, in the region occupied by the dust grains. Consequently, they constitute a novel type of dust ring current. Also for a given grain potential, size, and orbital distance, the grain velocity is known (equation (3)). Consequently, if the distribution and extent of the dust in a ring are known the total current carried by the ring can be estimated from

$$I(\text{esu}) = \frac{33{\cdot}3}{\pi}\frac{\phi(v)}{R_g(\mu)}\int_{L_1}^{L_2} v_{\text{rel}}\,\sigma\,\mathrm{d}l, \tag{9}$$

where v_{rel} is the relative velocity between the grains (all assumed to be of radius $R_g(\mu)$) and the plasma, and σ is the normal optical depth of the ring. It is once again stressed here that the plasma particles in the Debye sphere surrounding the charged dust do not move with the dust grain, but are constrained by the magnetic field to co-rotate.

Hill and Mendis (1982c) have used (9) to estimate the current carried by the F-ring of Saturn assuming that $R_g = 0{\cdot}5\ \mu$ and estimating that $\phi = -40$ V. They obtained a total current of about 10^5 A, which is sufficient to change the magnetosphere magnetic field noticeably up to about 100 km above the rings.

Subsequently, Ip and Mendis (1983) have shown that the diurnal modulation of the grain potential by Saturn's shadow will also cause a change in the dust-ring current near the terminators. Continuity of the current there requires that this dust ring current be connected to the planetary ionosphere by field-aligned Birkeland current and to close through the inosphere *via* Pedersen currents as illustrated schematically in figure 4, for

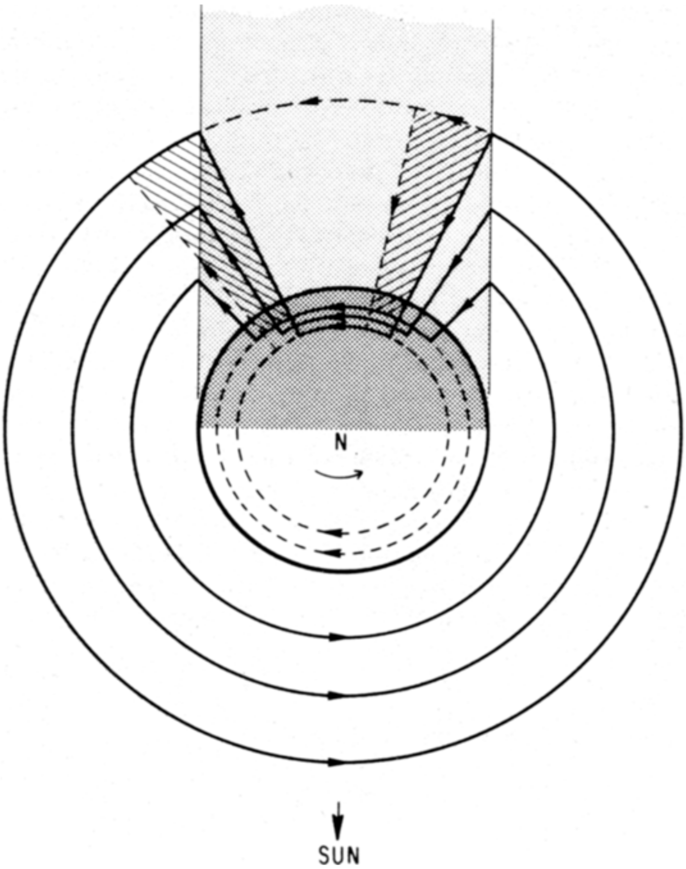

Figure 4. Idealized current system of Saturn's *D*-ring, corresponding to grains having a small positive electrostatic surface potential on both the day and night sides. The cross-hatched areas show where the Birkeland currents largely flow. The current system would be reversed if the grains had a negative potential or if they were charged to a very large positive potential (which is unlikely) (from Ip and Mendis 1983).

grains having positive potentials. If the grains were negative, the sense of the current system is reversed. These authors have considered, in particular, the modulation of the dust-ring current associated with the innermost *D*-ring ($1{\cdot}11 \lesssim L \lesssim 1{\cdot}23$) and have shown that a Pedersen current of the order of 10^5 A could be generated, which in turn sets up ionospheric electric fields of the order of $0{\cdot}1\ \mathrm{Vm}^{-1}$. It has also been pointed out that even if a significant fraction of the associated potential drop across the ionosphere is mapped along the field lines (which, of course, need not be equipotentials when parallel currents flow) onto the equatorial plane, the corresponding *E*-field would drive strong magnetospheric convection near the *D*-ring. This is a good example of the electrodynamic coupling between the rings and the ionosphere. Another example may be associated with formation of the spokes. When field aligned currents are set up near the terminators, large localized potential drops ("electrostatic double-layers") may be set up along these field lines, high up in the ionosphere (*e.g.* see Alfvén 1982). The beaming of energetic electrons, accelerated in such double layers, onto the ring plane, may give rise to the sporadic charging of the ring bodies to large electrostatic potentials and the consequent electrostatic blow-off of grains lying on their surfaces. The observed fact that a large fraction of the spokes seem to be formed in the region 3·00–7·00 local time, which is just outside the shadow of Saturn, supports this mechanism for their formation.

A very important cosmogonic consequence of dust-ring currents has recently been pointed out by Houpis and Mendis (1983). The dusty plasma analog of the well-known finite-resistivity "tearing" mode instability in such a dust current sheet has been shown to tear up a dust disc into ringlets with widths and separation typically of the order of the thickness of the disc. The authors also show that this instability grows much faster than any other type of instability such as the one induced by viscous diffusion in a differentially rotating disc. Consequently, they have suggested that this process, occurring at cosmogonic times, is responsible for the initial breakup of the primordial Saturnian proto dust disc into the multitude of kilometer thick ringlets that have been observed by the Voyagers 1 and 2 spacecraft.

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