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Discussion of the Pioneer 11 observations of the F ring of Saturn

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The photopolarimetric and charged particle data from the Pioneer 11 Saturn encounter were used as diagnostic tools in a preliminary analysis of the physical nature of the F ring of Saturn. It is argued that the F ring may have two components, with the outer one composed of solid particles of centimetre-diameter and the inner one of micrometre-sized dust particles. Also, the outer component as scanned by the charged particle detectors may have two rings instead of one. The double-ring option, if verified, could have interesting implications for the dynamical origin of the planetary ring systems.

Among the many exciting new results from the recent Pioneer 11 flyby of Saturn[1,2] one of the major findings is the discovery of a new (F) ring located at 2.33 R_s (Saturn radius) just outside the A ring by the Imaging Photopolarimeter (IPP) team[3]. The absorption effects of trapped charged particles by this ring were subsequently detected by the particle experiments[4–7]. According to the IPP observations, the F ring has a width of no more than 800 km and an optical depth of $\leqslant 2\times 10^{-3}$. In comparison with the whole saturnian ring system the F ring is very narrow indeed. Interestingly, there may be structures of even smaller scale in the F ring. First, the IPP team found indication of clumpiness in the ring. Second, the charged particle absorption features (the electron data, in particular) displayed distinct variations between 2.34 R_s and 2.36 R_s (refs 4, 5). These structures, if reflecting the condensation of matter around the F ring, would mean the presence of one or more rings (or satellites) with dimensions between 100 and 200 km.

Clearly, the particulate distributions are basic to the understanding of the F ring structure and the charged particle absorption taking place there. While some considerations on the nature of the F ring have been given by the Pioneer 11 experimenters[4,5,7], and by Dermott *et al.*[8]) in connection with their theoretical study of the narrow rings of Jupiter and Uranus, a more detailed ring model will be constructed here taking advantage of the published IPP and charged particle results. As planetary ring absorption is likely to play an important part in the budget of trapped radiation in the magnetospheres of Jupiter and Uranus as well as that of Saturn, we take the F ring as an example to outline some of the essential points of interaction between the planetary rings and the magnetospheric plasma. In particular we will explore the possibility of deducing the physical nature of the planetary rings from a combination of the optical and charged particle observations.

The most interesting F ring absorption features concern the sharp minima at 2.340 and 2.355 R_s observed in both of the inbound and outbound passes together with a central dip in the electron flux of 10 MeV energy range, which was detected only in the inbound pass[4,5]. Briefly, such absorption structures could be produced by three different (idealized) combinations of the ring system:

(1) One single circular ring in a dipole field with certain equatorial offset ($\Delta r \approx 0.01\ R_s$);
(2) One single elliptical ring in a dipole field with negligible equatorial offset ($\Delta r \ll 0.01\ R_s$);
(3) Two circular rings in a dipole field, again, with negligible equatorial offset.

The first two cases are essentially similar and the actual situation may be intermediate between them (that is, one single elliptical ring in a dipole field slightly offset with $\Delta r \leqslant 0.01\ R_s$, see Dermott *et al.*[8]) and this class of ring models will be illustrated by considering case (2). As shown in Fig. 1, charged particles drifting at different L shells would traverse different lengths of the ring material and hence experience varying degrees of reduction in particle flux[9]. As a result of such a longitudinal sampling effect, a radial profile of the absorption feature would be quite non-uniform with absorption minima formed at the inner and outer edges of the sweeping corridor of the ring. If we assume that the absorption profiles (such as locations and widths of the absorption dips) should have a certain correspondence with the radial variation of the integrated mass density or effective optical thickness, some physical parameters of the F ring may be derived. For instance, a plausible choice in which case the ring particles are bound by two orbits with $a_1 = 2.3500\ R_s$, $a_2 = 2.3479\ R_s$, $e_1 = 0.00468$, $e_2 = 0.00415$, and that the lines of apsides of these two orbits are aligned, could give a reasonable fit to the Chicago data[4]. Note that the maximum width of the F ring is about 200 km and the minimum only 50 km here, while the absorption effect extends over a region of 1,400 km. Such a ring configuration resembles the ε ring of Uranus[10–13], and by the same token this narrow ring is most likely maintained by a small satellite[8]. Whilst the double absorption minima flanking the ring are caused by the effect of longitudinal sampling of the charged particles, a sharp drop in the particle flux due to local absorption would also be observed if the spacecraft is situated in the near vicinity of the satellite or the main body of the ring (as may be the case for the inbound pass).

Some estimate for the optical thickness of the absorbing particles may be obtained by examining the two absorption minima. As outlined before[7,14–16], the cumulative reduction effect as the charged particles diffuse inward across a radial distance ΔL can be expressed by the survival probability given as:

$$P = \exp(-2N_b\tau) \qquad (1)$$

Where N_b is the total number of bounces executed by the charged particles and τ the effective optical depth of the absorbing particles with diameter larger than the absorption range R (~ 5 cm). Defining the radial diffusion time scale as:

$$t_d = \frac{(\Delta L)^2}{4D} \qquad (2)$$

(D is the radial diffusion coefficient), and the bounce period t_b is taken to be 2.4 s as appropriate for the 10 MeV electrons. Then with the relation $N_b = t_d/t_b$ plus using $\Delta L \approx 200$ km we find

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$\tau \leqslant 3.4\times 10^{6} D$ as $P\approx 5\times 10^{-2}$ at the outer absorption minimum observed in the outbound pass[4]. Since no more than 20% of the ring material will be sampled in one drift the actual relation should read: $\tau \leqslant 0.8\times 10^{7} D$.

Only upper limits of D have been given [$D<10^{-8}\,R_s^2\,s^{-1}$ at 3.1 R_s, or $D<6\times 10^{-7}\,R_s^2\,s^{-1}$ at 3.1 R_s and $10^{-7}\,R_s^2\,s^{-1}$ at 2.5 R_s (ref. 7)]. Consider that the radial diffusion coefficient in the saturnian magnetosphere might have a very steep L-dependence as in the case of the Earth's magnetosphere ($D\propto L^{10}$, see ref. 17), it is possible that $D\leqslant 10^{-9}\,R_s^2\,s^{-1}$ at the position of the F ring; thus $\tau\leqslant 0.8\times 10^{-2}$. This value is compatible with the value of $>5\times 10^{-5}$ as derived from using a somewhat different method[7], and with the IPP result of $\leqslant 0.8\times 10^{-2}$ if the width of the ring is taken to be 200 km.

Although these values appear to be in satisfactory agreement, the diffusion time scale (t_d) as determined by equation (2) is probably too short in comparison with the drift period of the 7–17 MeV electrons in question (that is, 3×10^{3} s compared with 7×10^{4} s). In other words, two narrow rings with complete coverage at all longitudes [that is case (3)] might be required instead of just one with partial longitudinal coverage which allows rapid refilling of the absorption dips. To this binary ring system we should add another satellite orbiting between them with semimajor axis $a\approx 2.35\,R_s$ and eccentricity $e\approx 0.004$.

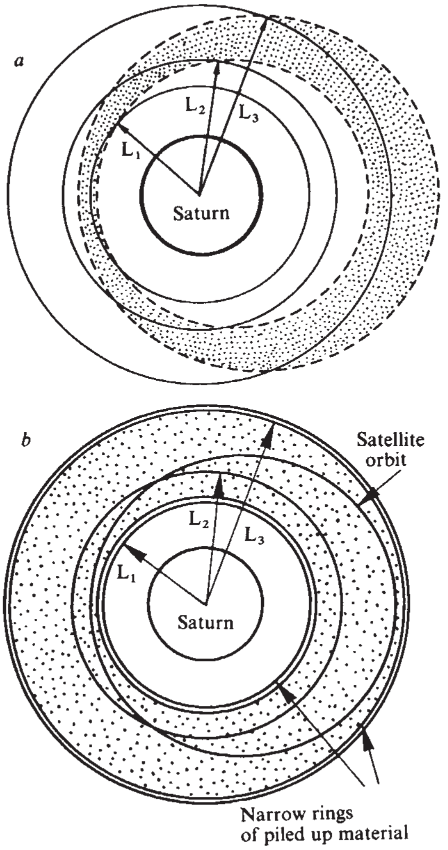

Fig. 1 Sketch of two possible ring configurations to interpret the observed charged particle absorption effects. *a*, One single ring with certain eccentricity and varying width. The charged particles drifting in different L shells would penetrate through different mass of ring material resulting in the formation of sharp absorption minima near perihelion and aphelion. If the diffusion time scale across the ring width is too short the absorption dips due to such longitudinal sampling effect could be refilled at certain positions. *b*, Two circular rings flanking the orbit of a small satellite in elliptical orbit. Two absorption minima would always be imprinted at all longitudes in the charged particle fluxes. If the spacecraft passes directly above or below the ring or satellite, an absorption spike would be observed as well as the inner and outer dips. Also the dipole offset, assumed to be zero here, could actually have a value like a fraction of 0.1 R_s.

The physical basis for the formation of such a system may be depicted as follows. After the fragments are ejected from the satellite surface at low speeds as a result of meteoritic bombardment or tidal stress, they would first follow trajectories approximating that of the parent satellite. However, they will be gradually cleared away within the sweeping corridor of the satellite, because of recapture by the satellite, or inward and outward diffusion due to inelastic collision with the satellite or with other small particles. The process of orbital dispersion, in any case, cannot continue forever as it is limited by the collisional frequency and mass density distribution of the interacting medium. It can be easily seen then there will be material piled up at the regions just bordering with the perihelion and aphelion of the satellite. As the particles injected into these edges would all have near circular orbits as a result of prior inelastic collisions, no further orbital dispersion could occur[18]; in this way two narrow rings of dense matter would be formed confining a wider zone of more diffuse nature. Note that such an orbital equilibrium configuration has been discussed before by Hénon[19] but in a somewhat different context.

A clear choice of the F ring configuration is difficult, but the possibility of a binary ring system is emphasized here as it has the potential of shedding new light on the structures of the rings of Uranus and Jupiter.

Another apparent puzzle in the Pioneer data may have some implication on the structure of the F ring—there is no signature of absorption of charged particles at the central position (2.33 R_s) of the F ring as identified by the IPP team. Barring systematic error in the spacecraft position by a margin of 0.01–0.02 R_s for this moment, we would have to conclude that the F ring detected by the imaging experiment was not responsible for the charged particle absorption. This has several interesting implications about the F ring system.

First, in order to reduce its absorption power but amplify its cross section for light reflection the optical component of the F ring must consist mainly of tiny dust particles of submillimetre size if not smaller. To check this point let us note that the survival probability for charged particles diffusing across a belt of dust particles with average diameter $d\ll R$ can be written as:

$$P=\exp(-2N_b X/R) \qquad (3)$$

where $X=2d\tau/3$. Now, with $P\gtrsim 0.95$ as judged from the electron data[4,5,7] we have immediately $d\leqslant 5.2\times 10^{-3}$ cm if the ring width ΔL is about 800 km and $d\leqslant 2.1\times 10^{-2}$cm if $\Delta L\approx 200$ km. In the above calculation we have assumed $D\approx 10^{-9}\,R_s^2\,s^{-1}$ and $\tau\approx 2\times 10^{-3}(800/\Delta L)$. If the albedo α of these particles is smaller than unity d would be even smaller. In the extreme case of $\alpha\approx 0.05$, as was found for the uranian ring particles[20,21], we have $d\leqslant 3\times 10^{-4}$–$10^{-3}$cm. From this point of view, the F ring identified by the IPP experiment may be in fact a dust belt of micrometre-sized particles similar to the jovian ring[22,23].

Second, to boost the absorption power but limit the cross section for light reflection to a small value the ring particles between 2.34 R_s and 2.36 R_s must be of centimetre size if not larger. Also, to explain the absence of this ring in the optical observation a low albedo must be invoked. In this way an optical thickness of $\leqslant 3\times 10^{-3}$ (for $\alpha\approx 0(1)$) as required to interpret the absorption feature would be reduced to be $\leqslant 2\times 10^{-4}$ if $\alpha\approx 0.05$. Such a value of optical depth may be below the limit of optical detection. On dynamical grounds, particles of metre size or so are required to maintain the stability of the narrow ring configuration against Poynting-Robertson effect[24]. But is there reason for such a low albedo? Presumably so, as whatever volatile ices on the particle surface would be sputtered away by the energetic ions exposing the (carbonaceous chondritic?) core material of low albedo[25]. [A similar thing can be said of the particles at the outer edge of the A ring in which case there is a difference of about 0.02 R_s between the IPP result and the charged particle data[3–7].]

Finally, that the dust belt of micrometre-sized particles should be located inside of the narrow ring of larger particles is consistent with its being of fragmentation origin—as proposed for the jovian ring[26–29]. Note that the rings of both Jupiter and Uranus have been suggested to be the fragments of small satellites which are spiralling inwards towards the central planets. According to Dermott *et al.*[30], for instance, the reason for such orbital decay is basically that the synchronous orbits of both Jupiter and Uranus are outside the Roche limits, so satellites formed between these two positions would be pulled inward as a result of planetary tidal action. For Saturn, the synchronous orbit at 1.8 R_s is inside of the Roche limit at 2.3 R_s, so a reverse process might take place there—with small satellites accreted from condensations in the A ring being gradually pushed away from the planet. The F ring and its parent satellite are then manifestations of just such a process[26].

We have discussed here the possibility that the F ring may have two components: (1) the inner one mainly consisting of micrometre-sized dust particles (detected by the IPP experiment), and (2) the outer one of centimetre- to metre-sized bodies emitted from a small satellite (observed by the charged particle detectors). This scenario makes interesting comparison with the discovery of the ring system of Jupiter[22,23,31,32]. We have also investigated the possibility of deducing the ring configuration capitalizing on the radial profiles of the observed absorption features of the charged particles. Besides the more conventional configuration of one single narrow ring we find that a double-ring system is also a possibility—if not strictly required by the particle data. Detailed intercomparison of the Pioneer IPP, particles and fields observations may allow us to narrow down some of the uncertainties. Also, the Voyager I flyby in November, which follows essentially the same trajectory, should provide another set of valuable data. From analysis of charged particle experimental data, Simpson *et al.*[33] have concluded that the symmetric pair of the F ring absorption dips observed both inbound and outbound, is caused by two separate narrow rings; Gehrels[34] has found that the high colour index of the optical F ring is consistent with the idea that it is made of micrometre-sized dust particles.

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Order-modulated structures and the thermodynamics of cordierite reactions

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The determination of palaeo pressures and temperatures (*P*, *T*) in metamorphic belts is of fundamental importance to our understanding of large-scale physical processes in the Earth. Such determinations are made by comparing observed mineral assemblages with experimental data on their *P*, *T* stability fields[1], thus assuming that the experiments are an adequate model for the natural reaction. The characterization of the structural state of natural and experimental materials is particularly important in this context. This note demonstrates the effect of the state of cation order on the *P*, *T* slopes of metamorphic reactions involving cordierite, $(Mg, Fe)_2Al_4Si_5O_{18}$, an indicator phase in metamorphism. Particular emphasis will be placed on the mechanism of Al, Si ordering in cordierite in so far as it relates to the characterization of the degree of cation order and hence the configurational entropy contribution to the thermodynamics of cordierite reactions.

Mg-cordierite occurs in two polymorphic forms. In the high temperature hexagonal structure, stable above ~1,450 °C (refs 2, 3), the Al and Si atoms are distributed over two sets of tetrahedral sites—three T_1 and six T_2 sites per formula unit $Mg_2Al_4Si_5O_{18}$ (Fig. 1). The Al, Si distribution involves two Al and one Si atom disordered over the T_1 sites and two Al and four Si atoms disordered over the T_2 sites[4]. In the slightly distorted low temperature orthorhombic form the T_1 sites are split into two non-equivalent sites T_11 and T_16, while the T_2 sites are split into a set of three non-equivalent sites T_21, T_26 and T_23. Within this new structure the Al, Si atoms are able to form a completely ordered distribution (see Table 1).

Experiments carried out on the mechanism and kinetics of the hexagonal–orthorhombic transition in anhydrous Mg-cordierite confirm that the polymorphism is due to Al, Si ordering and furthermore demonstrate that in equilibrium conditions the ordering transformation is first order involving the discontinuous transformation from a disordered to a well ordered phase at temperatures below ~1,450 °C (refs 3, 5).

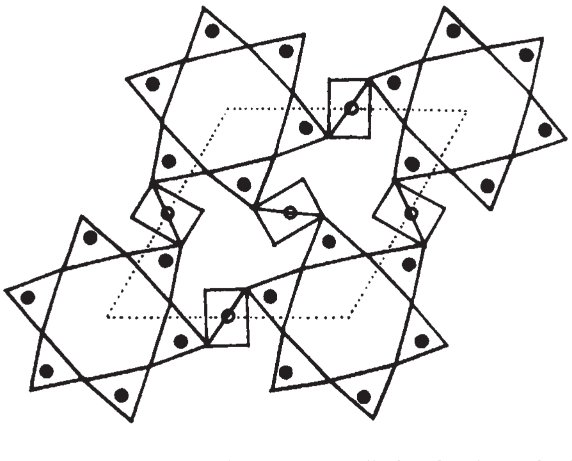

Fig. 1 The structure of hexagonal cordierite showing only the tetrahedral linkages. The tetrahedra in the ring sites (●) are designated T_2, while those outside the ring (○) are designated T_1 in Table 1. The dotted line is the hexagonal unit cell.

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