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Saturn's radio emissions: rotational modulation

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The unexpected rotational modulation of the Saturn kilometric radiation and Saturn electrostatic discharges, as revealed by Voyager 1 observations, are discussed in terms of a ring-current system and the geometry of the dipole field.

THE Saturn flyby observations of Pioneer 11 and Voyager 1 have revealed that the Saturnian ring system has important effects on the structures of the planetary ionosphere as well as the magnetospheric environment, such as the unexpected rotational modulation of the Saturn kilometric radiation (SKR) and the Saturn electrostatic discharge (SED) as discovered by the Voyager planetary radio astronomy experiment[1]. The emissions of the bursty and highly polarized SKR ($f < 1{,}200$ kHz) and the broad banded and unpolarized SED ($f \sim 20.4$ kHz–40.2 MHz) of impulsive nature strongly peaks at the subsolar longitude (SLS) of ~110°. The rotational control of the SKR and SED is a clock-like effect—with radiations preferentially emitted when Saturn has a particular phase relative to the Sun[1,2]. Although the sources of these radio emissions are not clear, Warwick *et al.*[1] argued that the SED emissions most likely originate in the rings of Saturn.

The challenge then is to devise a mechanism which can produce electrodynamic coupling between the ring system and the planetary ionosphere and/or magnetosphere in which the associated SKR and SED radio emissions are subject to longitudinal control. One obvious candidate is the establishment of field-aligned current systems—connecting the rings and the ionosphere with longitudinal variation. Local acceleration processes in the vicinity of the rings are also needed. Although the solution will probably have to await further observations and more detailed data analyses, we now discuss the interplay between the ring-current systems and the geometry of the dipole field and the rings and describe some of the basic ingredients in the longitudinal modulations of SKR and SED.

The Pioneer 11 radio measurements[3] and the Voyager 1 EUV experimental results[4] reveal that a strong coupling between the neutral hydrogen atmosphere of the rings with a number density of 400–600 cm^{-3} (refs 4–7) and the ionospheric plasma. Assuming the ionospheric H^+ ions have a number density of $n_i \sim 3\times10^3\ \text{cm}^{-3}$ near the ring plane, the pertinent charge-exchange loss time scale for the neutral H atoms can be estimated to be $\sim10^6$ s. Thus, for a total volume of the ring atmosphere to be $\sim3\times10^{30}\ \text{cm}^3$, the charge-exchange loss rate of the neutral atoms as a result of the $H^+ + H \rightarrow H + H^+$ process is $\dot{N} \sim 10^{27}\ \text{s}^{-1}$. This value is perhaps the most direct estimate for the source strength of the ring atmosphere and it supports the assessment by Carlson[8] that photo-sputtering of atomic hydrogen atoms from H_2O ice on the ring particles is responsible for supplying the observed H cloud of the rings, as other proposed effects[9,10] are far less efficient.

Note that 'the acceleration of the new ions (from charge exchange and other ionization effects) to co-rotation with the magnetosphere will necessitate the establishment of a so-called pickup current which flows radially outward outside the synchronous orbit (at 1.8 R_S) but inward inside this distance[11,12]. An order-of-magnitude approximation can be obtained by using $I \sim \dot{M}\Delta v/B\Delta x$ for the total current. Here $\dot{M}$ is the mass addition rate, B is the average magnetic field (~2,500 nT), $\Delta v \sim 1\ \text{km s}^{-1}$ is the difference between the corotating speed and the keplerian orbital speed, and Δx is the characteristic radial dimension of such a ring-current system. Even when the ionization rate of oxygen atoms is set equal to that of neutral H atoms, $I \leq 10^3$ A for $\Delta x \sim 1\ R_S$. This pickup current system is therefore relatively small, and not subject to rotational modulation.

Another current system is more promising. The near-perfect dipole field of Saturn has a slight vertical displacement (h) of the dipole centre from the planet's centre along the axial direction[13–15]. This enables charged particles to mirror just above the ring plane without being absorbed—a sort of plasma disk may be formed there. The longitudinal drifts (due to magnetic curvature force, gravity etc.) of the ions and electrons in this region would

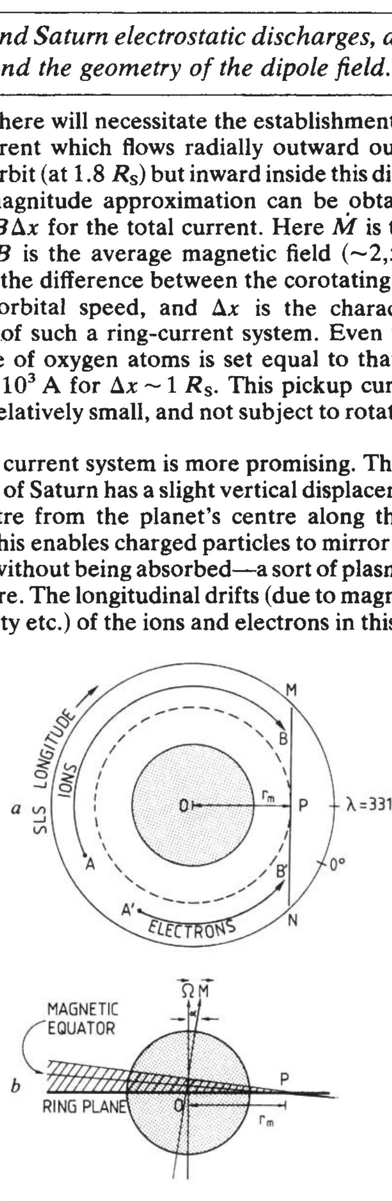

Fig. 1 *a*, Top view of the intersection between saturnian rings and the magnetic equator. The two planes intersect at $\overline{MN}$ and $\overline{OP} = 1.64\ R_S$ if the vertical displacement is 0.02 R_S and the tilt angle α is 0.7°. Inside the synchronous orbit r_{syn} at 1.8 R_S the ions drift west (A → B) and electrons east (A' → B'). Beyond r_{syn} they move in opposite directions. *b*, Side view of the above system. Particles with near 90° equatorial pitch-angle in the wedge-shaped 'free-zone' are not subject to any absorption.

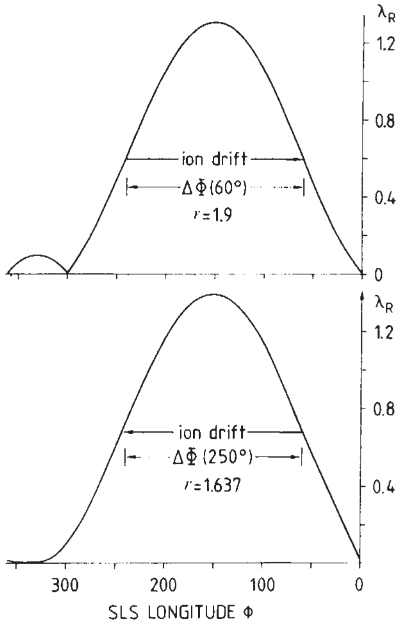

Fig. 2 The magnetic latitudes λ_r of the ring for $h=0.02$ and $\alpha=0.7°$ for two radial distances: *a*, $r=1.9\ R_S$; *b*, $r=1.64\ R_S$. Also indicated are longitudinal ranges of ions between ionization and ring absorption.

then constitute a current flowing in the azimuthal direction. At the same time, there is also a small tilt (α) of the dipole axis with respect to the spin axis of Saturn towards SLS longitude 331° (ref. 15). The important feature is that the magnetic equatorial plane and the ring plane intersect along a line which has its minimum distance from Saturn (r_m) at an SLS longitude of 331°. For $\alpha=0.7°$ and an offset of $h=0.02\ R_S$ (refs 13–15), $r_m=1.64\ R_S$. This combination of the vertical displacement and the tilt would cause the azimuthal currents to be interrupted at certain positions in the rings for $r>r_m$ (see Fig. 1). (For $r<r_m$ the magnetic latitude of the ring plane is always non-zero and some charged particles will therefore escape absorption by the rings. This disk-population may suffer from pitch-angle scattering through wave–particle interactions and become unstable.) Assuming that the mirror-latitudes of the ions do not change over a time scale of one longitudinal drift around the planet, their drift paths ($r\Delta\Phi$) can be determined by the difference between magnetic latitude (λ_r) of the ring plane and their mirror-latitudes (λ_m). Once the charged particles drift into the region with $\lambda_m>\lambda_r$, they would be absorbed. The variations of $\Delta\Phi$ for two radial distances are sketched in Fig. 2.

Assuming current continuity ($\nabla\cdot j=0$), the longitudinal variation of the azimuthal current ($j_\perp$) due to the mirroring effect would mean continuous diversion of the currents into the field-aligned components ($j_\parallel$). To estimate the field-aligned current at different longitudes (ϕ) the following relations are needed. First, the current continuity equation can be written as

$$j_\parallel=-\frac{1}{r}\frac{\partial}{\partial\phi}\int j_\perp\,dz \tag{1}$$

and second, the continuity equation for mirroring particles as

$$\frac{1}{r}\frac{\partial}{\partial\phi}(n_i v_d)=\frac{n_H}{\tau_i}-L_i \tag{2}$$

with $j_\perp\approx n_i e v_d$ where n_i is the ion number density at longitude ϕ, v_d is the drift velocity[16], n_H is the neutral H atom number density of the ring atmosphere (say), τ_i the ionization time scale and L_i the loss rate. Assuming that the ions can only mirror along the field lines in the region where $\lambda_r>\lambda_m$,

$$n_i\sim n_H\left(\frac{\tau_d}{\tau_i}\right) \tag{3}$$

where the longitudinal drift time scale between ionization and absorption is $\tau_d=r\Delta\Phi(\phi)/v_d$. Combining these relations, the field-aligned current density at longitude ϕ can be written as:

$$j_\parallel(\phi)\sim er\frac{\partial}{\partial\phi}\int_0^{\lambda_r(\phi)}\frac{n_H}{\tau_i}\Delta\Phi(\phi)\,d\lambda \tag{4}$$

Note that in the corotating system $\Delta\Phi>0$ if ions drift westwards towards increasing SLS longitudes (inside the synchronous orbit) and $\Delta\Phi<0$ if ions drift in the opposite direction (outside the synchronous orbit).

Contour plots of the field-aligned current density ($j_\parallel$) inside the synchronous orbit are shown in Fig. 3. Two maxima are found at SLS longitudes 120° (upward current from ionosphere to the ring) and 250° (downward current from the ring to ionosphere). Such field-aligned currents are corotating with the planet and if the ionization rate in this system is subject to diurnal variation, rotational modulation may conceivably result. For example, the escape flux of the ionospheric electrons reaching the ring at $L=1.6$ may have large day–night variation due to absence of photoelectron emission and cooling of the exosphere in the night side. (Note that an important nightside heat source, precipitation of energetic particles, does not exist at the latitudes magnetically connected to the rings as the rings are extremely good absorbers of energetic charged particles.)

But note that the azimuthal currents and the associated field-aligned components would be maintained, to a certain degree, even in the shadow of Saturn. This is because the ions produced in the dayside would continue to drift into the shadow to replenish the drift currents. The actual ionization rate must be largely determined by charge exchange between the neutral ring atmosphere and the planetary ionosphere as photoionization and electron impact ionization all have very long ionization time scales ($\gtrsim 10^9$ s). Using the minimum value of $\tau_i\sim 10^6$ s as appropriate for regions a fraction of a planetary radius from the ring plane, and a number density of 500 cm^{-3} for the hydrogen atoms) the peak flux (at SLS longitude 250°) can be estimated as $F_\parallel\sim 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$ in the equator and $10^7\ \text{cm}^{-2}\ \text{s}^{-1}$ near the top of the saturnian ionosphere. This is larger than the estimated photoelectron flux of $2\times10^5\ \text{cm}^{-2}\ \text{s}^{-1}$ from Saturn's ionosphere[10]. Thus the downward field-aligned current near SLS longitude 250° could become supercritical, particularly when it moves into Saturn's shadow. In such conditions, an electric field parallel to the magnetic field must be set up accelerating the ionospheric electrons away to maintain the downward current. The parallel potential drop could reach an absolute maximum equal to the total potential drop ψ across the current generating region.[17] This potential ψ arises from the fact that the field-aligned currents must close through the saturnian ionosphere which has a finite conductivity. According to Hill *et al.*[18] the total

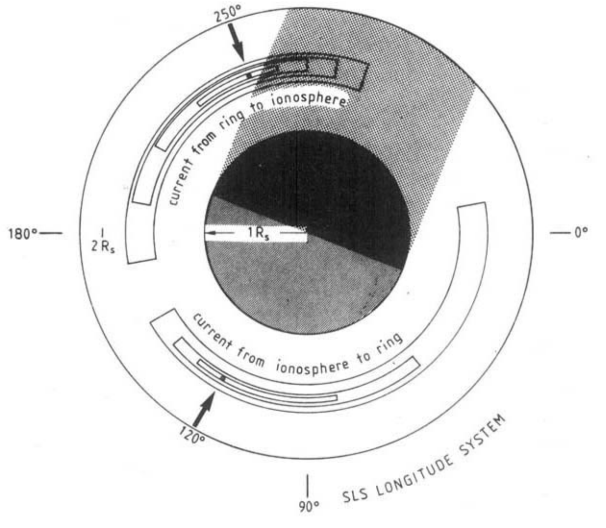

Fig. 3 Contour plot for the parallel electron flux (inside the synchronous orbit) associated with the field-aligned current system. Note that maximum flux from ionosphere to the ring occurs at SLS longitude 250° and the maximum flux from the ring to the ionosphere occurs at 120° SLS longitude.

potential drop across the longitude range $\Delta\Phi$ is

$$\psi = \frac{r\Delta\Phi}{\Sigma_p}\int j_\perp \, dz = \frac{I}{\Sigma_p}\frac{r\Delta\Phi}{\Delta r} \qquad (5)$$

Here Δr is the radial range of the field-aligned currents at radial distance r, $\Delta\Phi$ is the corresponding longitude range and Σ_p is the height-integrated Pederson conductivity of the planetary ionosphere. With the total current going through the ring system estimated to be $\sim 10^4$–10^5 A, $\Delta\Phi \sim \pi$, $r \sim 1.5\,R_J$ and $\Delta r \sim 0.3\,R_J$; $\psi = (0.15–1.5)/\Sigma_p$ (MV). Because Σ_p should be of the order of 1 S, if not less, the parallel potentials are conceivably quite large, that is of the order of a few keV.

Although the incorporation of SKR and SED radio emissions into this scheme is tempting but ambiguous a plausible scenario is offered below. We assume that a parallel potential of a few keV could be established in the shadow at SLS longitude 250° and that the ring particles are charged up to electrostatic potential of similar magnitude by the energetic electrons so generated. As soon as the ring particles move into the sunlight there will be immediate electrostatic discharge through emission of photoelectrons (accelerated to keV energies by the negative surface potential)[19]. The electrostatic energy stored on a 1-m radius ring particle charged to 10 keV is 10^{-2} J. Assuming no surface resistance the discharge time would be $\tau \sim 4\times10^{-8}$ s. The total power emitted by each ring particle is 2.5×10^5 W and should be broadband extending to a frequency of roughly $1/\tau \sim 25$ MHz. The maximum intensity of SED should then occur when the spot at SLS longitude 250° emerges from the shadow at which time the SLS longitude 110° faces the Sun (see Fig. 3). This is almost exactly the longitude at which the SED and SKR activities peak. (It is not clear whether the formation of radial spokes in the B ring as observed by the Voyager Imaging experiment[20] is related to this effect.)

SKR events still have to be explained and to a certain extent SKR may also depend on the SED. That is, as the broadband and bursty SED radiation propagates outwards, it will be absorbed by the dense plasma sheet between 4 and 8 R_S (refs 20, 21). If pitch-angle scattering of trapped energetic particles into the atmospheric loss cone is enhanced by plasma wave absorption, rotational modulation of SKR (in the desired manner) would follow. As there are sharp rises in the proton ($E_p <$ 2 MeV) and electron ($E_e < 0.43$ MeV) fluxes near the orbit of Dione[22], precipitation events triggered by the SED radiation must involve principally particles from that region. It is perhaps no great surprise that the SKR emission—besides the 10-h rotational modulation—also seems to be affected by Dione[2].

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Saturn's kilometric radiation: satellite modulation

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There is an episodic 66-h modulation of the Saturn kilometric radiation which is both frequency and Dione-phase dependent. The behaviour is significantly different from the way in which Io modulates the jovian emission.

THE discovery[1] of nonthermal (kilometric) radio emission (SKR) from Saturn by the Voyager planetary radio astronomy (PRA) instrument has raised the possibility of emission modulation by one or more of its satellites because Saturn, like Jupiter, contains satellites deep within a corotating magnetic field. However, examination of data extending from January to September 1980, yielded no Saturn analogue of the well-known Io-control phenomenon[2]. Instead, short-term (10 day) modulation of the SKR has been reported[3,4] at a period near 66 h, thus implicating satellite Dione as a possible agent. The nature of this modulation, if real, differs dramatically from the way in which Io controls the jovian emission. Using the PRA observations of Saturn, we here search for further evidence of episodic satellite control of SKR and examine the time evolution, frequency dependence and phase of the 66-h modulation. Results will be compared with the phenomenology of the jovian control by Io.

The earlier reports of modulation by Dione presented data in intensity/time format at Dione's revolution period. We will use the method of power spectral analysis to cast the results in a more objective light, although composite intensity–time dynamic spectra will also be used to illustrate graphically the material. The power spectrum method used is that of Deeming[5], and has been applied to the PRA data as described elsewhere[2].

Results

Figure 1 shows the results of power spectral analysis of SKR observed at 174 kHz between 28 October and 18 December 1980. This period of time brackets the Saturn encounter of 12–13 November. The spectrum spans the range of periods from just under 10 h to just above 100 h, corresponding to the range of expected periods of revolution of Saturn's five major innermost satellites and the planetary rotation itself. Aside from the dominant peak near 11 h, which corresponds to modulation of the SKR at Saturn's rotation period, no other statistically significant peaks are evident in the spectra, and, in particular,

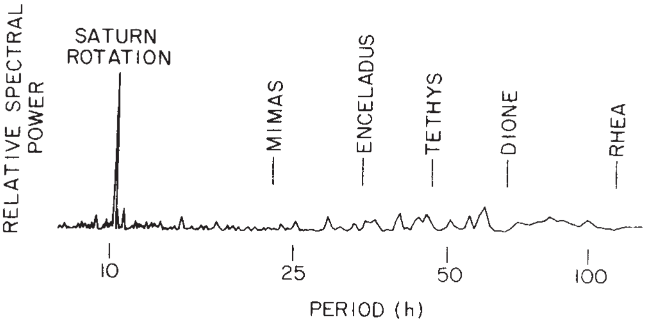

Fig. 1 The results of power spectral analysis of SKR observed at 174 kHz between 28 October and 18 December 1980. Only SKR events exceeding a flux density threshold of 2×10^{-21} W m^{-2} Hz^{-1} (normalized to a standard observer–Saturn distance of 1 AU) were used to eliminate a severe inverse-R-squared bias during this period. The only statistically significant modulation occurs at the 10.66-h Saturn rotation period.