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Control of Saturn's kilometric radiation by Dione

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Voyager 1 observations of Saturn's kilometric radio emissions reveal a strong but apparently transitory control by the orbital phase angle of Dione. This may be a geometrical effect and a time-variable plasma torus associated with Dione could explain most of the observed details of the Dione modulation by creating a shadow zone near the equatorial plane.

THE Voyager planetary radio astronomy investigation provided the first incontrovertible evidence of nonthermal radio emissions from Saturn[1]. The radiation spectrum peaks in the kilometre wavelength regime near 200 kHz and periodicities in the occurrence of the radio bursts give an internal planetary rotation period of 10 h, 39.9 min (ref. 2). Observations of the radio emission at 56.2 kHz by the plasma wave instrument on Voyager 1 revealed a modulation of the intensity of the radio emission with a period very close to the orbital period of Dione indicating that some control of the emission was a function of the orbital phase of the moon[3]. This control was also reported by the planetary radio astronomy investigation[4] with the maximum effect seen at lower frequencies[5], but extending as high as 385 kHz. The magnitude of the Dione influence is not constant in time and was strongest near closest approach. (Dione has a radius of 560 km (ref. 6) and is 6.29 R_S from Saturn in an orbit whose eccentricity is 0.002.)

Here we analyse the effect of Dione's orbital phase on the emission of radio waves from Saturn to explain the apparent transitory nature and suggest a mechanism for the interaction with the moon.

Nature of Dione's influence

We begin by describing the saturnian kilometric radio (SKR) spectrum below ~56 kHz. Figure 1 is a typical event as seen by the plasma wave instrument as Voyager approached Saturn on 11 November 1980. The amplitude of radio signals as a function of time for the upper five channels of the plasma wave spectrum analyser[7] are shown. The height of the solid black area represents the average power flux (W m^{-2} Hz^{-1}).

The radio burst shown in Fig. 1 increases in amplitude with increasing frequency to a peak at least as high as the upper frequency limit of the instrument (56.2 kHz). The emission is highly time-variable, changing in amplitude by nearly an order of magnitude on time scales of a few minutes. While gross amplitude changes track fairly well from one channel to the next, many of the fine-scale features are totally uncorrelated with those of adjacent channels indicating narrowband elements in the spectrum. Hence, the temporal variations of the SKR are similar in many respects to the auroral kilometric radiation from the Earth. The low-frequency cutoff of the saturnian emission has been reported[1] to be frequently near 60 kHz; however, Fig. 1 shows that the emission is detectable at frequencies as low as 10 kHz.

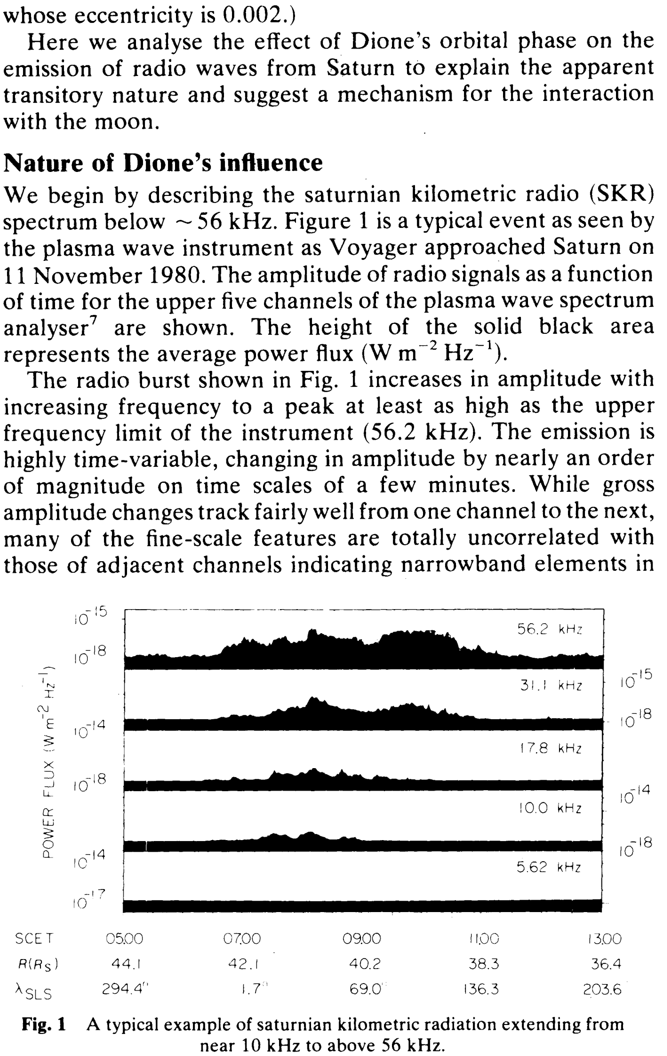

Fig. 1 A typical example of saturnian kilometric radiation extending from near 10 kHz to above 56 kHz.

We specifically consider the correlation between the orbital phase angle of Dione, ϕ_{Dione}, and the amplitude of the kilometric radio emission which was originally demonstrated by Gurnett *et al.*[3], who showed that in addition to the 10 h 39.9 min modulation related to Saturn's rotation, the emission was strongest when Dione was in the local dawn sector. Figure 2 plots the hourly average power flux of the radio emission at 56.2 kHz as a function of radial distance; also shown is a dashed line with a R^{-2} dependence. The arrows indicate times when Dione was at local dusk ($\phi_{\text{Dione}} = 270°$) and correspond to periods when there is little or no kilometric emission. Figure 2 suggests that the effect of Dione is to suppress or attenuate the saturnian radio emission when $\phi_{\text{Dione}} \simeq 270°$. (The nearly-constant minimum signal strength of $\sim 8 \times 10^{-19}$ W m^{-2} Hz^{-1} corresponds to the receiver noise level.) The peaks of the 10 h 39.9 min bursts approximately follow a R^{-2} dependence except for periods within ~200 R_S when the amplitude of the peaks fall well below the curve coincident with the passage of Dione through the dusk sector. Beyond ~200 R_S on the inbound leg and ~165 R_S on the outbound leg the periodic suppression in phase with Dione's orbital motion is no longer evident. The Dione suppression might explain the apparent north–south asymmetry in the source strength at lower frequencies reported by Warwick *et al.*[4] since Dione was near local dusk for most of Voyager 1's trajectory through southern latitudes.

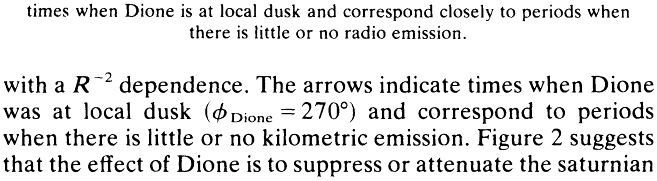

Fig. 2 A plot of hourly average values of the 56.2 kHz plasma wave receiver channel as a function of radial distance from Saturn. The narrow bursts are emitted at a period of ~10 h 39.9 min and generally rise in amplitude with decreasing R approximately as R^{-2}. The arrows indicate times when Dione is at local dusk and correspond closely to periods when there is little or no radio emission.

Analysis of traces similar to that in Fig. 7 of ref. 3, and the present Fig. 2, shows that a clear signature of the Dione modulation is not present before day 308 or after day 325 of 1980. These dates correspond to Voyager–Saturn distances of 227 and 165 R_S, respectively. To illustrate the transitory nature of the Dione effect further, we show the result of a statistical study of the occurrence of kilometric radiation as a function of Dione's

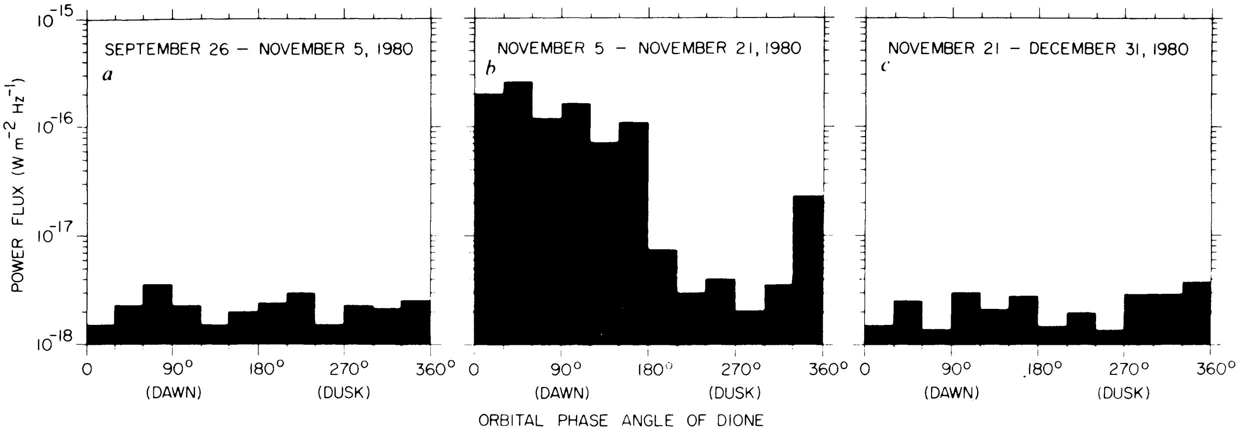

Fig. 3 Plots of the 98% amplitude as a function of Dione's orbital phase angle for the distant inbound, near encounter, and distant outbound Voyager 1 trajectories at 56.2 kHz. Note the strong Dione control near encounter and the complete lack thereof during the distant inbound and outbound passes.

orbital phase angle. The bar graphs in Fig. 3 show the power flux below which 98% of the samples fell for each of 12 phase angle bins. Recall that phase angle is measured positive eastward from a plane containing Saturn's rotation axis and the Sun, with 0° at local midnight. Figure 3*b* includes all data covered by Gurnett *et al.*[3] when the Dione effect is qualitatively most apparent. Figure 3*a*, *c* present results from the inbound and outbound legs when little or no Dione control was apparent. It is clear the distant inbound and outbound data show no significant trend. On the other hand, the difference in amplitude at the 98% level between phase angles near 90° and 270° is about two orders of magnitude for the two-week period near closest approach. For this period, Dione clearly has an important role in determining the amplitude of Saturn radio emissions at 56.2 kHz.

Discussion

There are many possible interactions by which a moon may influence the generation of magnetospheric radio emissions. We shall attempt to narrow the list of likely candidates to one or two which are consistent with all or most of the observations. We assume the SKR originates at relatively low altitudes on high latitude field lines, presumably in the auroral region as suggested by Kaiser *et al.*[8].

We first need to explain the transitory nature of the effect. A truly transient process which is active for two weeks and then inactive for long periods of time requires a mechanism to stimulate the control. The long-term studies show no Dione effect[4] so the active periods must be quite rare. Hence, it is strange that the effect was seen coincidentally with closest approach and we shall argue that the effect is not transitory but depends on the location of the observer.

The simplest explanation of the transitory nature of the Dione control is geometric in nature and specifically related to Voyager's low latitude or small distance from the equatorial plane of Saturn around closest approach. The effect became apparent around day 308 when Voyager 1 was at 8.3° latitude and about 33 R_S above the equatorial plane. On day 325, when the effect apparently disappeared, the spacecraft was at a latitude of 25.4° and 71 R_S above the equatorial plane. A second episode of Dione control in early December has been reported by the planetary radio astronomy team[5]. The effect is visible in the plasma wave data at 56.2 kHz, however, we are not confident in interpreting our data as a genuine Dione effect at this time. Should this be a valid episode, however, our conclusion of a geometric effect would be in jeopardy.

Figure 2 showed Dione attenuated the saturnian radio emission as opposed to stimulating or amplifying it. The attenuation could be caused by a propagation effect or by a basic change in the source itself. In either case, the most likely interaction mechanism is a change in magnetospheric density associated with the satellite. A decrease in density could only be accomplished by a sweep-up effect and this is hardly a time-variable process capable of disturbing the inner magnetosphere on time scales of a few days. An increase in magnetospheric density, however, is plausible as the result of a process which liberates particles from the moon making the moon a plasma source. This type of process occurs in the jovian system with Io being the primary source of plasma.

Frank *et al.*[9] argued that Dione could be a reasonable source for an oxygen torus at Saturn. A peak in the ion density at Dione's orbit with density and temperature profiles reminiscent of those at Io in Jupiter's magnetosphere suggests that Dione, like Io, is a plasma source. Also, the water ice or frost surface of Dione opens the possibility of plasma production through dissociation and ionization. A ledge-like structure in the plasma torus near Dione's L-shell has been reported[10], and similarities of this structure with that observed at Io in Jupiter's magnetosphere suggest a plasma source. Evidence from the Pioneer 11 magnetometer[11] also suggests a process involving plasma production. On the inbound Pioneer trajectory, significant magnetic field perturbation was seen at Dione's L-shell but no effect was observed on the outbound leg. Local time of Dione was ~ 21 h ($\phi_{\mathrm{Dione}} \sim 315°$) and ~ 1 h ($\phi_{\mathrm{Dione}} \sim 15°$) for the Pioneer inbound and outbound Dione L-shell crossing, respectively. Although there are several possible explanations, this magnetic field signature is consistent with a ring current associated with Dione which varies with ϕ_{Dione}.

An increase in magnetospheric density could affect radio emissions by modifying conditions at the source of the radiation. There is some evidence that the Earth's auroral kilometric radiation is quenched by increasing the density in the source region[12–14], however, Gurnett and Anderson[15] have stated that this is not very likely. Another difficulty with direct modification of the source is that the plasma produced at Dione would have to have easy access to the source. If the radio source were in the auroral region, it is unlikely that an equatorial plasma source at $L \sim 6$ could effectively modify the density in the auroral zone.

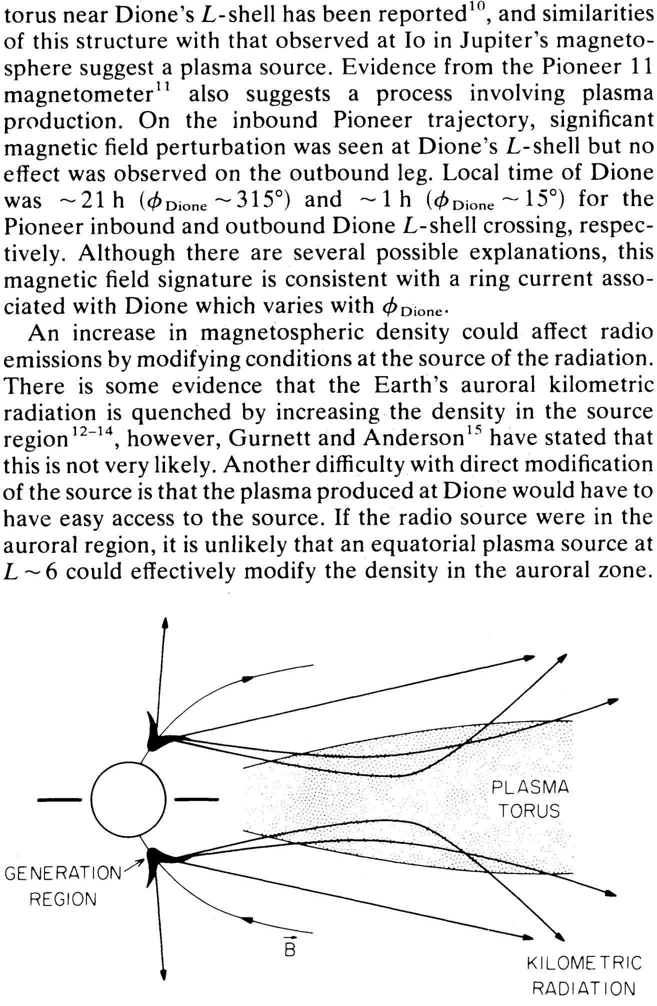

Fig. 4 How a Dione-related torus would refract radio waves from Saturn away from the equatorial region. A similar effect was found for broadband kilometric radiation from Jupiter.

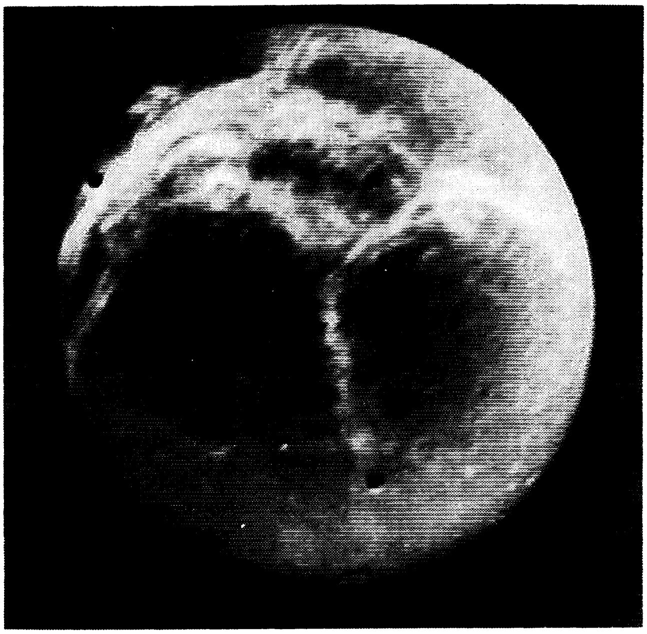

Fig. 5 An image of the trailing hemisphere of Dione taken by Voyager 1 when Dione was near local dusk. Note that this sunlit hemisphere is dominated by bright wispy features which are probably fresh outcroppings of water ice or frost. The frost may be a source of plasma for a torus whose density fluctuates with the same period as Dione's orbit.

The alternative is to assume that an increase in plasma density associated with Dione affects the propagation of radio waves through refraction or reflection as represented in Fig. 4. We used the model torus from ref. 3, although the model shown by Bridge *et al.*[10] would give essentially the same effect. Waves with frequency less than or equal to the local plasma frequency in the torus cannot penetrate the torus. Waves of higher frequency will be refracted away from the equatorial region, although the effect will diminish with increasing frequency.

Many observations suggest that the model shown in Fig. 4 is viable. First, the density of the plasma torus as measured by Pioneer 11 (ref. 9) and Voyager 1 (refs 3, 10) is of the order of 40 cm^{-3} corresponding to a plasma frequency of 57 kHz. Waves below this frequency could not penetrate the torus and waves well above 100 kHz could undergo substantial refraction. This refraction is consistent with the frequency dependence of the Dione effect reported by Desch and Kaiser[5], as lower frequencies tend to be refracted most. Second, because preliminary observations[3,10] suggest the plasma is confined near the equator, waves propagating near low latitudes would be most affected. Therefore, we expect a low-latitude shadow zone as was found for the jovian kilometric radiation[16,17]. A shadow zone near the equator would explain the presence of a Dione control only near encounter when Voyager 1 was close to the equator. The asymmetry in the latitude at which the effect appears and disappears could well be a local time asymmetry in the thickness or density of the torus.

How then does the orbital phase angle of Dione modulate the emission? It is important first to establish that the modulating effect of the torus is longitudinally symmetric. The evidence is embodied in Fig. 7 of ref. 3 and Fig. 2 of this paper. Note that the phase of the Dione effect did not change as Voyager moved from near local noon before encounter to local early morning after the encounter. If there were a localized cloud of plasma which orbited Saturn, a phase shift would have been apparent as the viewing point changed. As the phase did not change, the modulation effect must be longitudinally symmetric. This longitudinal symmetry should be fairly easily achieved due to the rapid corotation of the plasma which will quickly distribute plasma in longitude even though the source may be localized.

To explain the dependence of the torus density on the orbital phase angle of Dione, we suggest that Dione may be a plasma source only when it is near local dusk. Hence, the plasma cloud produced dissipates on a time scale of about a day so that by the time Dione is near local dawn the torus density has decreased by a factor of say, two. Because the trailing hemisphere of Dione is always the same, a hemispheric asymmetry in direct particle sputtering processes cannot explain the dawn–dusk asymmetry. On the other hand, there are obvious asymmetries in the surface features of Dione. Figure 5 shows Dione near local dusk. The trailing hemisphere shows a complex pattern of wispy features which do not appear on the opposite hemisphere of Dione. Smith *et al.*[6] suggest the bright markings are controlled by a regional system of fractures or faults possibly formed or reopened by internally generated stresses. The bright material is probably water ice and it is tempting to speculate that this relatively fresh surface frost is photosputtered when the trailing hemisphere is sunlit as it is when Dione is near local dusk, or that photodissociated volatiles produce the plasma.

Carlson[18] and Frank *et al.*[9] have discussed the rings as possible sources of plasma in the saturnian magnetosphere. Of processes such as photosputtering, ion sputtering, sublimation with subsequent photodissociation, and others, photosputtering seems to be the most efficient mechanism. It would be a convenient mechanism for an orbital phase-dependent source of plasma at Dione in view of the hemispherical asymmetry of the wispy features shown in Fig. 5. Taking the hydrogen atom flux derived by Carlson[18] of $\sim 10^{8}$ cm^{-2} s^{-1}, Dione can produce $\sim 10^{24}$ atoms s^{-1} (assuming the entire sunlit hemisphere is a source and photosputtering is applicable to Dione). If the time scales for both creation and dissipation of the plasma torus are $\sim$1 day (to provide a 2.74-day modulation period), then the production/loss rate must be the order of 10^{28} s^{-1}. We have assumed a torus 4 R_S thick, centred at 6 R_S, which fluctuates between 20 and 40 cm^{-3}. Obviously, photosputtering is not sufficient to produce a dense torus on the time scale of a day.

If we assume that the other processes considered by Carlson are no more efficient than photosputtering, we must consider a mechanism which is based on the release of volatiles from fractures in Dione's crust and subsequent photodissociation. Presumably the volatiles would be released into the exosphere at a constant rate but preferentially from the wispy hemisphere. Photodissociation of the molecules would occur only during the dusk sector of Dione's orbit when the wisps are sunlit. This mechanism is largely speculative and production rates depend on rate of volatile release, the type of volatile, and photodissociation rate. However, the injection rate at Io has been estimated[19] at $2 \times 10^{29 \pm 1}$ ions s^{-1}, about 200 times that required at Dione.

The proposed fluctuating torus model also requires a dissipation rate of the order of 10^{28} s^{-1}. Richardson *et al.*[19] point out that outward radial diffusion through flux-tube interchange is the predominant loss mechanism at Jupiter and given that oxygen or some other heavy ion is an important constituent of the Dione torus[9,10] the centrifugally-driven interchange instability is likely to be important at Saturn, also.

We have arrived at a model which is similar in part to effects observed at Jupiter. We propose that Dione is responsible for the production of plasma when it is near local dusk which forms a longitudinally symmetric torus. The torus then casts a radio shadow on low latitudes so that the saturnian radio emission cannot be seen by a spacecraft near the equator. The torus decays with a time constant of about one day so that as Dione approaches local dawn the usual saturnian emission reappears. The possibility of an additional Dione-control episode[5] in early December, 1980 at $\phi_{\text{Dione}} \sim 40°$, however, presents an even more perplexing situation to be explained involving a shift in the phase of the control.

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