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Narrowband electromagnetic emissions from Saturn's magnetosphere

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A series of narrowband electromagnetic emissions were detected by the plasma wave instrument on board Voyager 1 coming from the inner region of Saturn's magnetosphere in the frequency range 3–30 kHz. These emissions have many similarities to continuum radiation detected in the Earth's magnetosphere and narrowband kilometric radiation in the jovian magnetosphere. The observed frequency spacing suggests that the emissions are being generated near Tethys, Dione and Rhea, probably in regions of large plasma density gradients associated with boundaries of the plasma sheet.

During the Saturn flyby the Voyager 1 plasma wave instrument observed a series of narrowband electromagnetic emissions at frequencies between 3 and 30 kHz (ref. 1). These bands are remarkable because of their extremely complex spectral structure, consisting of a large number of nearly monochromatic emissions with frequency spacings corresponding to the equatorial electron gyrofrequencies near the moons Tethys, Dione and Rhea. Because of the possible association of the radio emissions with the moons of Saturn, we have analysed these emissions to determine their origin and to explore similarities to other planetary radio emissions. We describe here their characteristic and discuss models of the generation of these emissions (the plasma wave instrumentation is described in ref. 2).

Observations

The strongest and best resolved examples of the narrowband electromagnetic emissions occur in the inner region of the magnetosphere, near closest approach. The electric field intensities in this region are shown in Fig. 1. Each channel gives the electric field intensity on a logarithmic frequency scale at the centre frequencies indicated on the left of the plot. The electron gyrofrequency, f_g, and plasma frequency, f_p, are also shown for reference. The electron gyrofrequency ($f_g = 28B$ Hz, where B is the magnetic field in nT) was determined from the Voyager 1 magnetic field instrument[3], and the plasma frequency ($f_p = 9{,}000\sqrt{n_e}$ Hz, where n_e is the electron number density cm^{-3}) was obtained from the Voyager 1 plasma instrument[4]. The narrowband electromagnetic emissions consist of a series of smooth enhancements in the 3.11–31.1-kHz channels from about 21 h 00 min (spacecraft event time) on 12 November to 01 h 00 min on 13 November. These enhancements all occur at frequencies above the electron plasma frequency as determined by the plasma experiment. The sharp cutoffs evident in the 5.62- and 10.0-kHz channels shortly after closest approach seem to be directly associated with the local electron plasma frequency. The enhanced intensities extend across the electron gyrofrequency with no obvious propagation effect. These characteristics identify the mode of propagation as the free-space left-hand polarized ordinary $(L, 0)$ mode. For this mode propagation occurs for all frequencies $f > f_p$, and that no resonance or cutoff occurs at the electron gyrofrequency.

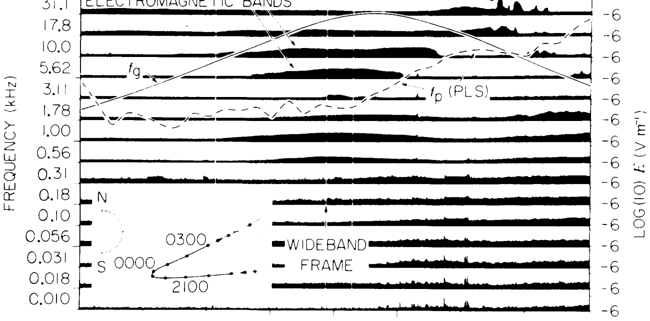


Fig. 1 The plasma wave electric field intensities in the region near closest approach. The narrowband electromagnetic emissions are confined to the low density region outside of the plasma sheet at $f > f_p$ (dashed lines). The plasma sheet is entered at about 00.00 to 01.00, as the spacecraft approaches the magnetic equator (see trajectory sketch).

Another type of very intense narrowband emission occurs in the 31.1-kHz channel of Fig. 1 at about 01.30 on 13 November, coincident with the cutoff of the electromagnetic radiation. At peak intensity this narrowband burst has a field strength ~60 db larger than the adjacent radiation. Based on similar observations in the Earth's magnetosphere[5-7] and at Jupiter[8-10] this burst is identified as an electrostatic emission at the local upper-hybrid resonance (UHR) frequency, $f_{UHR} = (f_p^2 + f_g^2)^{1/2}$. The fact that the observed emission frequency is higher than the upper hybrid resonance frequency computed from the measured plasma frequency and gyrofrequency is attributed to uncertainties in the determination of the electron number density. The electron plasma frequency is a factor of ~3 higher than given by the plasma instrument at this particular time.

Because the intensity of the electromagnetic radiation is comparable in adjacent frequency channels, Fig. 1 implies that the spectrum is nearly continuous, possibly comparable with the continuum radiation detected in the Earth's magnetosphere[5]. Fortunately, one 48-s frame of wideband waveform data obtained in this region provides greatly improved frequency resolution. The high-resolution spectrum of the wideband data (Fig. 2) is not continuous, but rather consists of many narrowband emissions, some with bandwidths <100 Hz. Three main bands can be identified at frequencies of ~1 kHz, ~6 kHz, and ~9.7 kHz. Because the low-frequency band at 1 kHz is below the electron plasma frequency, whereas the others are all above it, this band cannot be propagating in the same mode as the higher frequency bands. For $f < f_p$ the only possible modes are the whistler-mode and the z-mode. Based on the similarity to whistler-mode hiss emissions observed in the higher density regions of the plasma sheet, we concluded that this low-frequency (~1 kHz) band is propagating in the whistler mode[1].

The most definitive evidence that the high-frequency bands are propagating in the free-space electromagnetic mode is given in Fig. 3, which shows a series of wideband spectrograms obtained over a 3-day period near and after closest approach. A single persistent band of emission can be seen at ~5 kHz extending over a range of radial distances from at least 3.26 to 58.3 R_S. Because the plasma parameters change over a wide range it is difficult to see how this band of emission could be observed over such a large range of radial distance without being a freely propagating electromagnetic wave. The last observation, Fig. 3 F, is in the magnetosheath where the local plasma

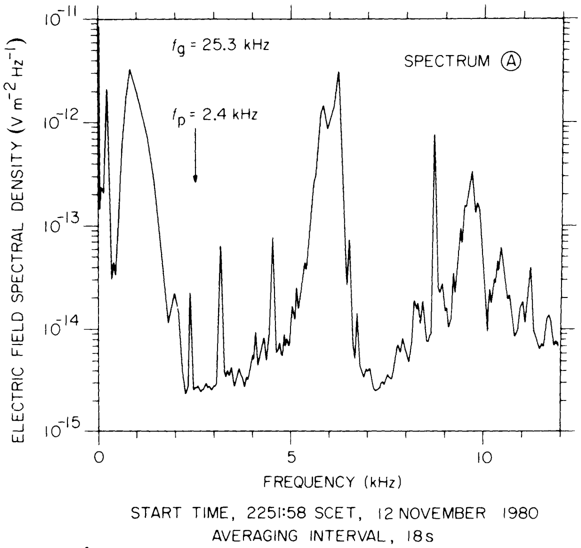


Fig. 2 A detailed frequency spectrum of the emission in Fig. 1, showing the occurrence of numerous bands with approximately harmonic frequency spacings.

frequency is ~ 3.8 kHz [J. Scudder, personal communication]. Although the electromagnetic bands can be detected in the wideband data over several days, the intensity and detectability vary considerably. The meridian plane plot in Fig. 4 summarizes the regions in which the bands were detected. Except for the brief interval near closest approach all of the emissions were confined to high latitudes on the outbound pass. None were found on the inbound leg and this is almost certainly due to the fact that the spacecraft was passing through the high density central region of the plasma sheet where the electron density is high enough to refract the radiation away from the equatorial region. In contrast, for the outbound pass ($R \gtrsim 10\ R_S$) at high latitudes the electron density[4] is always low enough to allow direct line-of-sight propagation to the spacecraft at frequencies above a few kHz. The strongest emissions were observed at position A near closest approach, suggesting that the radiation originates in the inner region of the magnetosphere at $R \lesssim 10\ R_S$.

Examination of the 16-channel survey plots shows evidence of a periodic modulation of the narrowband emission intensities at the 10 h 40 min rotation period of Saturn. Typically, the narrowband emission events last for ~ 3 or 4 h and tend to recur at intervals of ~ 11 h. The three intervals containing B, C–D, and E, in Fig. 4 show this periodicity. Maximum intensity occurs when the Saturn longitude system (SLS) longitude of the sub-satellite point is near 290°. Event F in Fig. 4 is also in phase with this general rotational modulation, however, one cycle seems to have been missed between E and F, possibly owing to the very low intensity and difficulty of detecting these emissions far from the planet.

Relationship to other planetary radio emissions

Although the complex narrowband structure of these Saturn radio emissions appears unusual, very similar types of radio emissions have been identified in the magnetospheres of Earth and Jupiter. At Earth a relatively weak type of broadband radio emission called continuum radiation is generated within the magnetospere[5,11,12]. This has a relatively smooth steady temporal structure, and when analysed with spectral resolution comparable with that of the Voyager 16-channel analyser, the overall appearance is very similar to the emissions shown in Fig. 1. When the terrestrial continuum radiation is analysed with better frequency resolution it becomes apparent that the spectrum is not continuous, but instead consists of a series of discrete narrowband emissions[13]. The detailed characteristics of the continuum spectrum depend on the frequency range. At frequencies below the solar wind plasma frequency, where the radiation is trapped in the low-density magnetospheric cavity, the spectrum tends to be nearly continuous with only occasional narrowband structure[11]. At frequencies above the solar wind plasma frequency, where the radiation can freely escape from

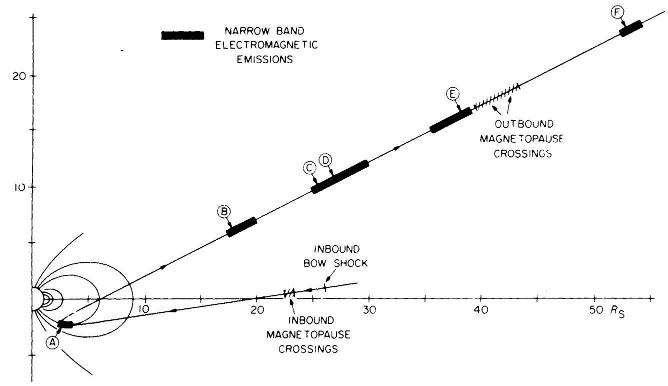
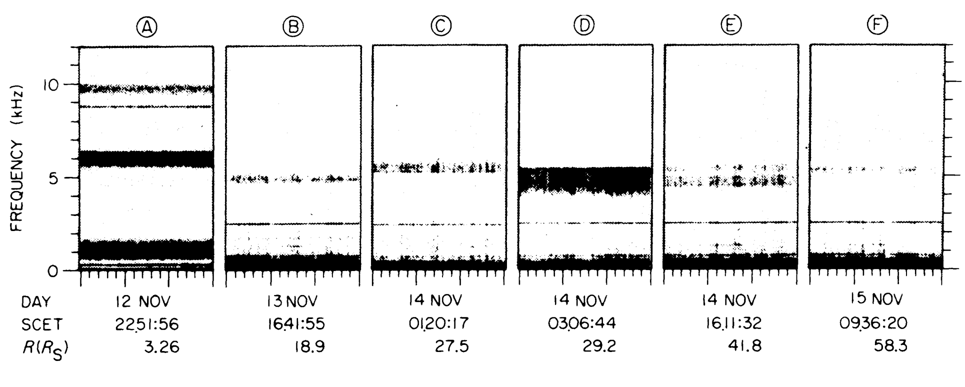


Fig. 4 A summary of regions where narrowband electromagnetic emissions were observed. The black bands indicate detections in the 16-channel spectrum analyser data, and the circles correspond to the wideband spectrograms shown in Fig. 3.

the magnetosphere, the frequency spectrum usually shows considerable narrowband structure. Typically, it consists of several relatively broad emission bands consisting of numerous narrowband features, some of which have harmonic frequency spacings[13]. The spectral characteristics of the terrestrial narrowband emissions are remarkably similar to those observed at Saturn.

At Jupiter narrowband electromagnetic emissions (narrowband kilometric radiation (nKOM)) with similar characteristics have been reported by Kaiser and Desch[14]. Although the frequency resolution available for the jovian nKOM observations is not sufficient to reveal the extraordinary fine structure evident in the terrestrial and saturnian emissions, the overall characteristics are quite similar. In particular, the jovian nKOM intensity is controlled by the rotation of Jupiter, very similar to the rotational control of the narrow-band emissions observed at

Fig. 3 Frequency–time spectrograms obtained in various regions of the magnetosphere demonstrating that the band at ~5–6 kHz can be detected over a large range of radial distances. This series of observations provides the best evidence that the noise consists of freely propagating electromagnetic radiation.



Saturn. The period of the nKOM is slightly slower than the rotation period of Jupiter, and corresponds to the rotation period of the plasma in the outer region of the Io plasma torus[14], at a radial distance of about 10 R_J.

The close similarities between the narrowband electromagnetic emissions at Earth, Jupiter, and Saturn strongly suggest that the same basic emission mechanism operates at all three planets. At Earth it is now widely believed that continuum radiation is generated by mode conversion from electrostatic waves generated by low-energy electrons. This general mechanism has a long history of experimental and theoretical development[5,7,15,16], including the observation of enhanced radiation intensities when low-energy electrons are injected into the magnetosphere[17]. The electrostatic wave involved is an electrostatic mode which occurs near the upper hybrid resonance frequency, $f_{UHR}=(f_p^2+f_g^2)^{1/2}$. One of the specific conditions which must be satisfied for this mode to be unstable is that $(n+1/2)f_g \simeq f_{UHR}$ (refs 6, 7, 18). The physical situation in the Earth's magnetosphere is illustrated in Fig. 5, which shows a representative radial profile of f_{UHR} and f_g near the plasmapause. Intense electrostatic emissions occur whenever f_{UHR} crosses a half-integral harmonic of f_g (dashed lines). Kurth *et al.*[13] have demonstrated that the electrostatic emissions are directly converted to electromagnetic radiation with little or no frequency shift. The radiation is generated in the free space (L, 0) mode. The resulting radio emission spectrum therefore consists of a series of lines with a frequency spacing characteristic of the electron gyrofrequency in the source region. Kurth *et al.*[13] have proposed that the jovian nKOM radiation can be explained by essentially the same mechanism, with the density gradient in the outer region of the Io plasma torus having the same role as the plasmapause at Earth. Large plasma density gradients are an essential element of some theories for the electrostatic to electromagnetic mode conversion[19].

Interpretation of Saturn observations

Because of the close similarities between the narrowband radio emissions at Earth, Jupiter and Saturn, the electrostatic to electromagnetic mode conversion mechanism probably also accounts for the narrowband emissions at Saturn. This view is supported by the fact that intense upper hybrid waves are observed at Saturn in the region where the narrowband electromagnetic radiation is most intense (see Fig. 1). Also, at Saturn these emissions are known to be propagating in the free space (L, 0) mode—the favoured mode for mode conversion. But the exact source location and the physical processes which lead to the generation of intense electrostatic waves remain uncertain.

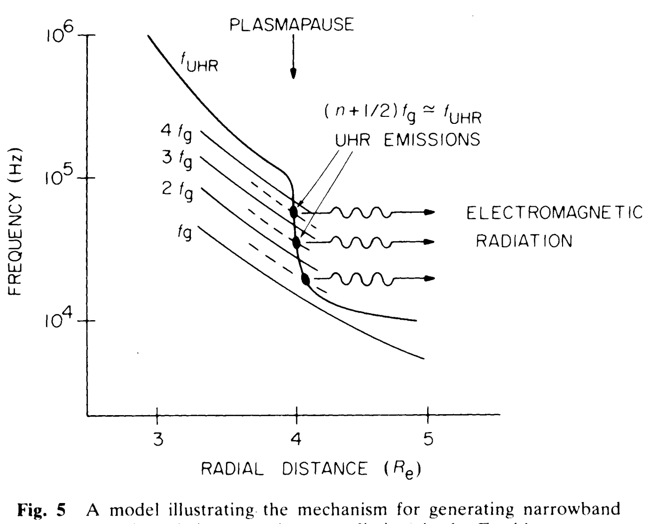


Fig. 5 A model illustrating the mechanism for generating narrowband electromagnetic emissions (continuum radiation) in the Earth's magnetosphere. Intense electrostatic upper hybrid resonance (UHR) emissions at $(n+1/2)f_g \simeq f_{UHR}$ are believed to be converted to electromagnetic emissions in regions with steep plasma density gradients, such as near the plasmapause.

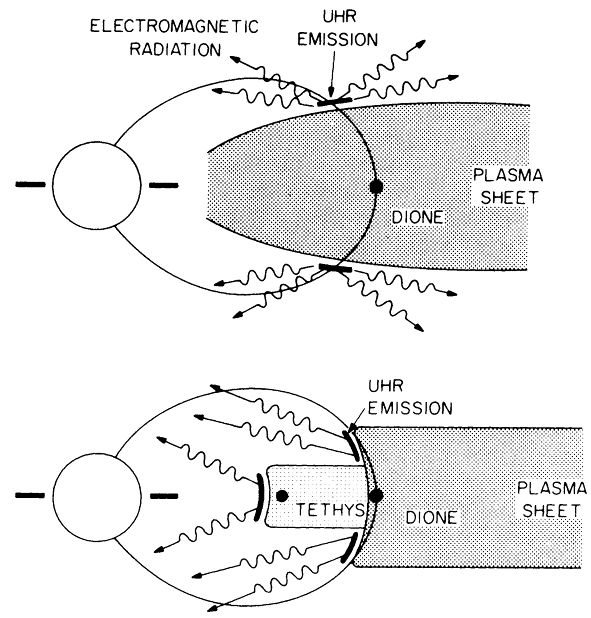


Fig. 6 Two possible models for generating narrowband electromagnetic emissions in Saturn's magnetosphere. *a*, The emissions are generated at the density gradient which exists at the north and south boundaries of the plasma sheet; *b*, the emissions are generated along the field-aligned boundaries of the plasma sheet[4].

Unfortunately, because of no appreciable tilt in the magnetic dipole axis of Saturn, there are no geometry-dependent propagation effects to help determine the source location. Probably the best clue is the frequency spectrum. If the mode conversion model is correct then the frequency spacing between the lines is approximately the electron gyrofrequency in the source region. Figure 2 shows that several half-integral harmonic frequency spacings can be identified in the radio emission spectrum. If we identify the main emissions at 6.0 and 9.7 kHz as a harmonic pair, then the gyrofrequency is 3.7 kHz. A second set of lines can be identified at 3.1, 4.7 and 6.1 kHz, which gives a gyrofrequency of 1.50 kHz. Finally, a third set of lines at 8.7, 9.6, 10.4 and 11.4 kHz gives a gyrofrequency of 870 Hz. Assuming that the source is located near the equatorial plane (as at Earth and Jupiter) the corresponding radial distances for these gyrofrequencies are 5.4, 7.3 and 8.8 R_S, based on a dipole moment of 0.21 G R_S^3 (ref. 3). Note that depending on the plasma density gradient in the source region and the location of the source relative to the magnetic equator, the observed emission frequencies may not occur at exact half-integral harmonics. Therefore, these radial distances should be regarded as only a rough indication of the source position. The radial distances obtained are in the vicinity of Tethys, Dione and Rhea. Because at least one of Saturn's moons, Dione, is already thought to have an important role in controlling Saturn's kilometric radio emissions[1,20,21], this comparison strongly suggests that one or more of these moons is involved in generating the narrowband electromagnetic emissions.

The most likely way a moon could control nonthermal radio emission processes in the inner region of Saturn's magnetosphere is by injecting plasma much as Io controls radio emissions by injecting plasma into the jovian magnetosphere. Evidence from the Pioneer 11 and Voyager 1 plasma instruments[4,22] suggests that plasma production by Tethys and Dione may be the source of the extended disk-shaped plasma sheet observed near the equatorial plane of Saturn. If nonequilibrium processes associated with the plasma injection are responsible for the narrowband electromagnetic emissions, then the analogies with Earth and Jupiter would suggest that the source is associated with a steep plasma density gradient near the edge of the plasma sheet. Figure 6*a*, *b* shows two extreme models for the source positions. In Fig. 6*a* the source is located near the north–south boundaries of the plasma sheet, and in Fig. 6*b* near the sharp field-aligned inner boundary of the plasma sheet described by Bridge *et al.*[4].

If the source is located as in Fig. 6*a* then it would have to be tightly confined to a specific L-shell to produce the narrow emission spectrum. Such a localization could, for example, be caused by a field-aligned current system flowing along the Dione L-shell. A source located on the Dione L-shell at the north–south boundary of the plasma sheet 2 R_S from the equatorial plane would have an electron gyrofrequency in close agreement with the 3.7-kHz major frequency spacing evident in Fig. 2. On the other hand, if the source is located along a field-aligned inner boundary of the plasma sheet then the narrowband characteristic of the source would be easily explained as the gyrofrequency is, to first order, constant along the magnetic field line near the equator. This situation could be closely analogous to the generation of continuum radiation near the plasmapause at the Earth, except that the decreasing density gradient is facing towards rather than away from the planet. Note that the 7.3 R_S radial distance identified for the 1.5 kHz frequency spacing in Fig. 3 closely agrees with field-aligned boundary identified by Bridge *et al.*[4] at $L = 7$. This boundary occurs slightly beyond the orbit of Dione. Because of uncertainties concerning the plasma density distribution in the inner region of the magnetosphere, it is too early to decide which can best account for the characteristics of these emissions.

Conclusion

The Voyager 1 flyby of Saturn has revealed narrowband electromagnetic emisssions originating from the inner region of the magnetosphere. At closest approach the broadband electric field strength of these emissions is $\sim 50\,\mu V\,m^{-1}$, which corresponds to a total radiated power of about 2.5×10^6 W, assuming an isotropic source. Although this is small compared with the power radiated by Saturn at kilometric wavelengths, $\sim 10^8$–10^9 W (ref. 20), these emissions are of interest because of the close similarity to narrowband radio emissions from Earth and Jupiter.

Comparisons with similar emissions in the Earth's magnetosphere suggest that they are produced by mode conversion from electrostatic waves near the upper hybrid resonance. This radio emission mechanism has also been proposed to explain certain types of solar radio emissions[23]. Although the basic mechanism has been identified, the conditions in which the radiation can occur are poorly understood. Observations at all three planets suggest that distinct 'hot spots' occur from which the radiation is preferentially emitted. The association of the source with a plasma density gradient may be a requirement for the mode conversion process[19]. Unfortunately, the requirements for generating the electrostatic waves are not completely understood. The generation of these waves probably involves the presence of large fluxes of low energy (100 eV to 1 keV) electrons with a pronounced loss-cone or $\partial f/\partial v_\perp > 0$ feature and a suitably large cold-to-hot electron density ratio[18,24,25]. The apparent control of the narrowband emission intensities by Saturn's rotation presumably provides an important clue to the processes involved. However, because of the very close alignment of the dipole axis with the rotational axis of Saturn[3], it is not clear how this rotational control is imposed.

Finally, at Saturn no evidence was found for trapped continuum radiation comparable to the continuum radiation trapped in the low density magnetospheric cavity of Earth and Jupiter. As the Voyager 1 plasma measurements[4] demonstrate the existence of a low-density cavity at Saturn with an electron plasma frequency well below the solar wind plasma frequency, it is surprising that no radiation is trapped in this cavity. The radio emission source at Saturn does not seem to extend down to sufficiently low frequencies to illuminate the cavity. The reasons for this marked difference in the radio emission spectrum are not understood.

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