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Narrowband electromagnetic emissions from Jupiter's magnetosphere

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Recent studies of wideband plasma wave data from Voyagers 1 and 2 have revealed the existence of narrowband radio emissions escaping from Jupiter's magnetosphere in the frequency range 1–12 kHz. These narrowband emissions are very similar to narrowband emissions previously discovered near Earth and Saturn, and are believed to be produced by mode conversion from locally generated upper hybrid resonance waves at odd half-integral harmonics of the electron cyclotron frequency. This mode conversion process is believed to be one of the basic mechanisms for generating planetary radio emissions.

DURING the Voyager 1 and 2 flybys of Jupiter, the plasma wave instrument detected a series of narrowband electromagnetic emissions at frequencies between ~1 and 20 kHz, in a frequency range where the radiation can propagate freely away from the planet. These emissions are remarkable because the spectral structure is extremely complex, consisting of many closely spaced lines, and because similar types of narrowband electromagnetic emissions are known to be generated in the magnetospheres of Earth[1] and Saturn[2,3]. The frequency spacing of these radio emissions suggests that they are produced by electrostatic upper hybrid resonance waves at odd half-integral harmonics of the electron cyclotron frequency. This type of locally generated electrostatic wave is believed to be responsible for the narrowband emissions observed at Earth[1] using a mode conversion process. The mechanism for generating the narrowband electromagnetic emissions therefore appears to be a universal one, with possible applications to solar and other astrophysical radio sources. We now describe the characteristics of the jovian narrowband emissions and discuss possible mechanisms for generating the emissions.

Observations

An example of the jovian narrowband electromagnetic emissions is illustrated in Fig. 1 which shows a survey plot of the electric field intensities obtained from the 16-channel spectrum analyser during the inbound Voyager 1 pass through the jovian magnetosphere on 3 March 1979. The narrowband emissions show up in these plots as a relatively smooth feature in the 10.0-kHz channel from about 08 h to 10 h SCET (spacecraft event time) at a radial distance of about 42 R_J. The narrowband character of the radiation can only be discerned by the use of high resolution spectrograms from the wideband electric field waveform data, such as shown in Fig. 2. These spectrograms, which consist of a sequence of 15-s intervals spaced a few minutes apart from about 9 h 40 min to 10 h 8 min, show that the radiation consists of a series of closed spaced narrowband emissions, each with a bandwidth of only a few hundred Hz, or less. These narrowband features are known to be freely propagating electromagnetic radiation because they occur well above the electron plasma frequency, f_p, in a frequency range where the only mode of propagation is the free space electromagnetic mode. The electron plasma frequency can be determined from the trapped continuum radiation, which is known from wideband measurements to have a low frequency cutoff at the local electron plasma frequency[4]. The electron cyclotron frequency, f_c, which is the only other relevant frequency of the plasma is ~400 Hz in this region, well below the electron plasma frequency.

The sequence of spectrograms in Fig. 2 shows that although the narrowband emissions do not change significantly during the 15-s duration of the spectrogram, marked changes occur during the several minute interval between spectrograms.

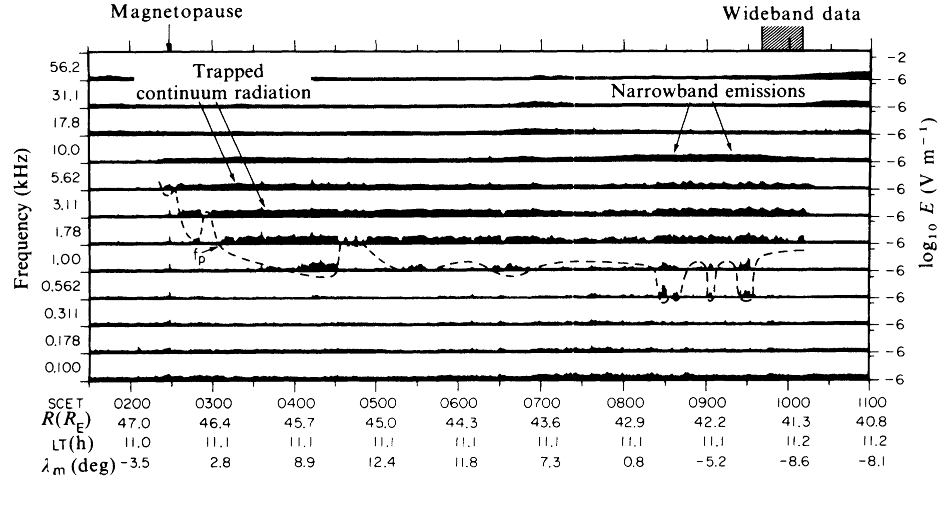


Fig. 1 The electric field intensities from the 16-channel spectrum analyser on Voyager 1 during the inbound pass through the jovian magnetosphere 3 March 1979. The narrow-band electromagnetic emissions occur in the 10-kHz channel. The dashed line indicates the electron plasma frequency, $f_p = 9\sqrt{n_e}$ kHz, where n_e is the electron number density in cm^{-3}.

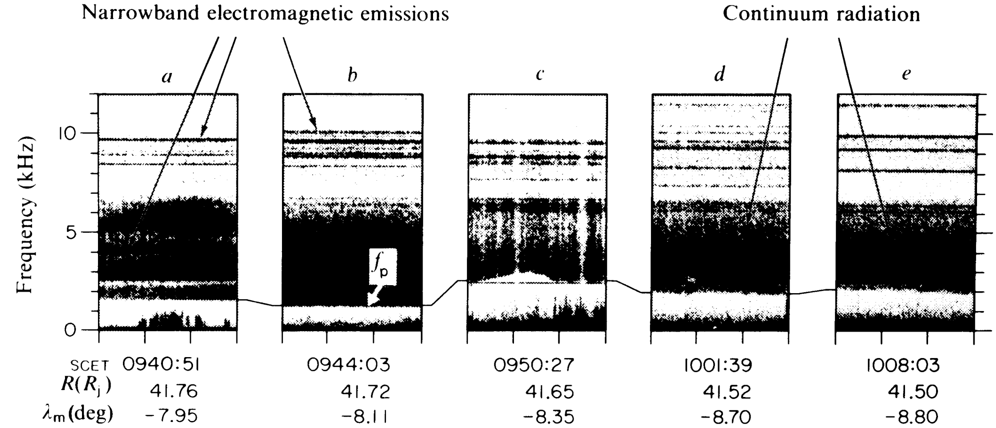


Fig. 2 High-resolution wideband spectrograms showing that the 10-kHz emission in Fig. 1 consists of many closely-spaced narrowband emissions. The broadband emission just above the plasma frequency, f_p, is continuum radiation trapped in the low density magnetospheric cavity.

Unfortunately, because gaps occur in the wideband data[5], it is not possible to follow the detailed temporal evolution. However, the spectrograms give the strong impression that the source consists of a large number of isolated lines between about 8 and 12 kHz, each of which is changing intensity on a time scale of a few minutes. The electric field strengths of the most intense bands range from about 10 to 30 $\mu V m^{-1}$. Occasionally, as in Fig. 2*d* at 7.4, 8.3 and 9.2 kHz, a series of lines can be identified that have a nearly constant frequency spacing, suggesting that the emission frequencies are harmonically related. In addition to the lines around 10 kHz another series of lines can be seen at lower frequencies in Fig. 2*a* superimposed on the trapped continuum radiation. These lower frequency emissions, which are shown in greater detail in Fig. 3 at 2.7, 4.1 and 5.4 kHz, also have a harmonic frequency spacing. Similar narrowband features have been previously reported in the trapped continuum radiation at Jupiter[6]. The lines in the trapped continuum radiation are usually not as narrow and sharply defined as the emissions observed above the continuum radiation.

At present, three events have been identified near Jupiter with characteristics of the type described above. The second of these events occurred during the outbound Voyager 1 pass through the magnetotail on 6–7 March 1979, at a radial distance of about 32 R_J. The spectrum analyser data for this event are shown in Fig. 4. The narrowband emissions in this case sweep downward in frequency, starting in the 17.8-kHz channel at about 22 h on 6 March and ending in the 5.62-kHz channel at about 3 h on 7 March. A sequence of spectrograms illustrating the narrowband character of these emissions is shown in Fig. 5. In this case the spectrograms have a 4-s duration and are separated by roughly half-hour intervals. Again the spectrum is characterized by many closely spaced lines with a tendency for harmonic frequency spacings. The downward drift in the average frequency is clear. The temporal variations of the individual lines are very complex. Some of the lines decrease in frequency with increasing time, whereas others remain at a fixed frequency, varying in intensity as the main band sweeps across the emission frequency. The downward frequency drift continues until the lines merge into the trapped continuum radiation below ~5 kHz.

The third event was obtained during the Voyager 2 approach to Jupiter on 4 July 1979, at a radial distance of 71.5 R_J, very close to magnetopause. This case, shown in Fig. 6, has very clear evidence of harmonic structure with a frequency spacing of about 200 Hz. Also, evident in the same region is a series of narrowband upper hybrid resonance (UHR) waves. From previous observations[6] these waves have been identified as an electrostatic mode at the local upper hybrid resonance frequency, $f_{UHR} = (f_p^2 + f_c^2)^{1/2}$. The upper hybrid waves occur at discrete frequencies separated by the electron cyclotron frequency. Figure 6 shows that the upper hybrid waves occur at the same frequency as the narrowband electromagnetic emissions, which strongly implies that the escaping electromagnetic radiation is being generated by these locally generated electrostatic waves.

Because the jovian decametric radiation[7] and kilometric radiation[6,8], are controlled by the rotation of Jupiter and tend to occur in a fixed longitude range, it is interesting to investigate the longitude at which the narrowband emissions occur. For the events on 3 March and 6–7 March the System III (1965) longitude of the spacecraft was 332° ± 36° and 4° ± 105°, respectively. For the event on 4 July the System III (1965) longitude was 314°. No longitude limits can be given for the third event because the duration cannot be accurately determined from the 16-channel survey data. These longitudes all fall in the same general region, centred on roughly 336°, suggesting that the rotation of Jupiter may have some control on the occurrence of these emissions. However, with only three events available for study, it is difficult to determine the strength of this rotational control.

Discussion

These observations of jovian narrowband electromagnetic emissions confirm the existence of the same type of radio emission process at three planets: Earth, Jupiter and Saturn. The similarity between the jovian and saturnian narrowband emissions is quite striking. At Saturn the wideband spectrograms show a series of narrowband emission lines[2,3] with characteristics essentially identical to those illustrated in Figs 2, 3 and 5. At Earth wideband spectrum measurements with the ISEE 1 spacecraft show essentially identical narrowband

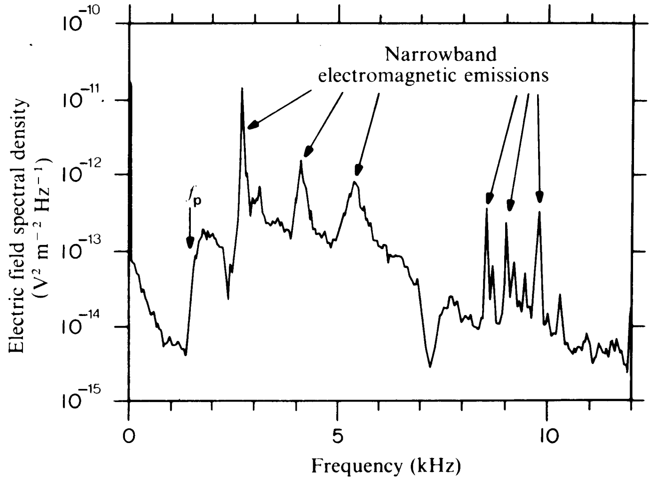
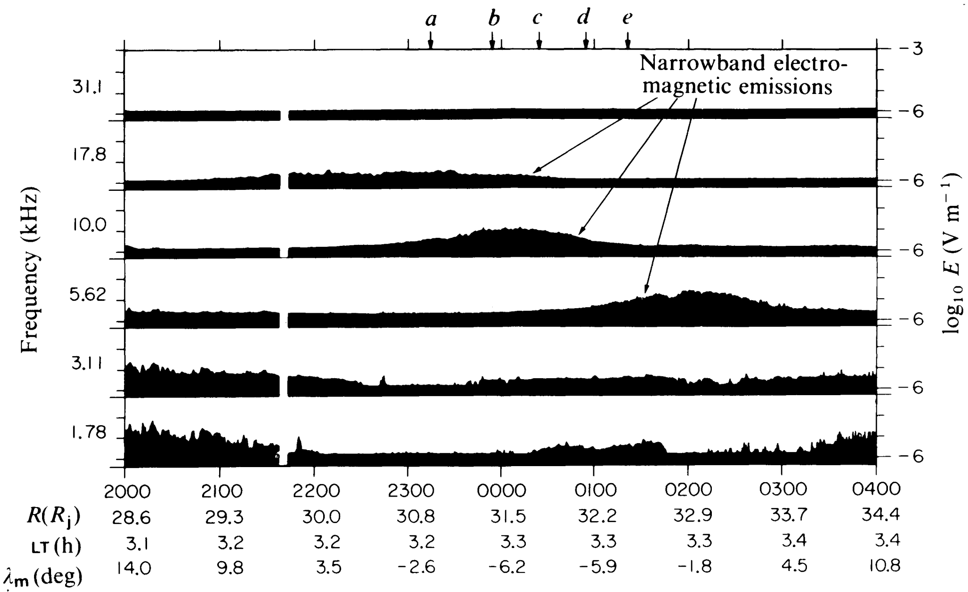


Fig. 3 A representative electric field spectrum for the event in Fig. 2*a* at 0940: 48 SCET; 18-s average; $R = 41.7\ R_J$; $\lambda_m = -8.1°$; LT = 11.1 h. This spectrum is remarkably similar to the spectrum of the narrowband electromagnetic emissions observed at Saturn[3].

Fig. 4 The 16-channel spectrum analyser data from Voyager 1 during the outbound pass through the magnetotail 6–7 March 1979. The narrowband emissions occur in the 17.8-, 10.0- and 5.62-kHz channels, sweeping downward in frequency with increasing time.



emission lines (see Fig. 7 of ref. 1). The jovian narrowband emissions may also be similar to a type of jovian radio emission called narrowband kilometric radiation (nKOM) that has been previously reported by Kaiser and Desch[9] from the planetary radio astronomy (PRA) instrument on Voyager. The nKOM usually consisted of an enhancement in a few channels near 100 kHz, above the frequency range (1–12 kHz) of the emissions described here. It seems likely that if better frequency resolution were available from the PRA instrument it would be found that the nKOM actually consists of many closely spaced emission lines similar to those illustrated in Fig. 3.

The best evidence of the origin of the narrowband electromagnetic emissions comes from terrestrial measurements, where a long series of observations indicates that the radiation is produced by electrostatic electron cyclotron waves near the upper hybrid resonance frequency[10–12]. The upper hybrid resonance instability occurs when the upper hybrid resonance frequency is near an odd half-integral harmonic of the electron cyclotron frequency, $f_{UHR} \simeq (n+1/2) f_c$, where n is an integer[12–15]. The free energy for the instability is produced by a region of positive slope, $\partial f/\partial v_\perp > 0$, in the electron distribution function, such as occurs in a ring or loss-cone distribution. The instability is enhanced by the presence of cold electrons.

The physical situation that is believed to be responsible for generating the narrowband emissions in the jovian magnetosphere is illustrated in Fig. 7, which shows a representative radial profile of the upper hybrid resonance frequency and the electron cyclotron frequency near the equatorial plane. Because the plasma is moderately dense near the equatorial plane the upper hybrid resonance is nearly the same as the electron plasma frequency, $f_{UHR} \simeq f_p$, and is therefore determined by the electron density profile. The dashed lines are the odd half-integral harmonics of the electron cyclotron frequency. The electrostatic waves occur at the points where the dashed lines cross the upper hybrid resonance frequency. Observations in the Earth's magnetosphere show that the electrostatic waves are converted directly to electromagnetic radiation with little or no frequency shift[1]. The mode conversion process could be either a linear escape mechanism associated with density gradients, of the type suggested by Oya[16] and Jones[11], or a nonlinear two-wave interaction, of the type discussed by Melrose[17]. Because of the quantized frequency spectrum of the upper hybrid waves, the escaping radio emissions consist of a series of lines with a quasiharmonic frequency spacing, the exact frequencies of which are determined by the details of the electron density and magnetic field profiles. Because the electron density at Jupiter is often very irregular (note the variations of f_p in Figs 2 and 5), the emission frequencies are undoubtedly much more complicated than indicated by Fig. 7, thereby accounting for the large number of lines and great complexity of the spectrum. Observations in the Earth's magnetosphere indicate that the source of the narrowband emissions is very patchy[1], consisting of numerous isolated regions, each emitting a frequency determined by the plasma parameters associated with that region.

As indicated in Fig. 7 the narrowband emissions can, in principle, be generated either on the rising part of the electron density profile in the inner magnetosphere or in the region of rapidly decreasing density near the magnetopause. The line spacing of the emissions in Fig. 6 (~200 Hz) is characteristic of the electron cyclotron frequency in the outer region of the magnetosphere, which suggests that these emissions are generated at or near the magnetopause. The radiation is then emitted inward, towards the planet, as shown in Fig. 7. In other cases, such as in Figs 2 and 5, the emission frequency extends to frequencies so high, well above 10 kHz, that a magnetopause source is impossible. In these cases the radiation is emitted outward, from a source in the inner magnetosphere. If the emission frequency is below the magnetopause plasma frequency, then the radiation is permanently trapped inside the low density magnetospheric cavity. This radiation can then account for the trapped continuum radiation, as has been

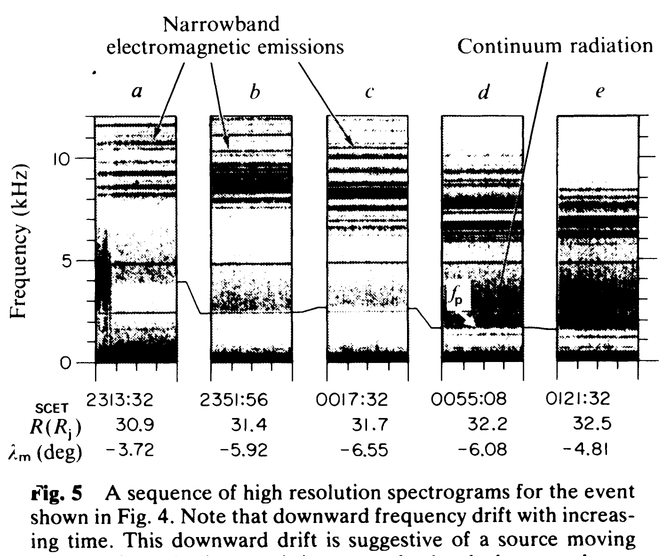


Fig. 5 A sequence of high resolution spectrograms for the event shown in Fig. 4. Note that downward frequency drift with increasing time. This downward drift is suggestive of a source moving outward from Jupiter, emitting near the local electron plasma frequency as the source moves to increasing radial distance.

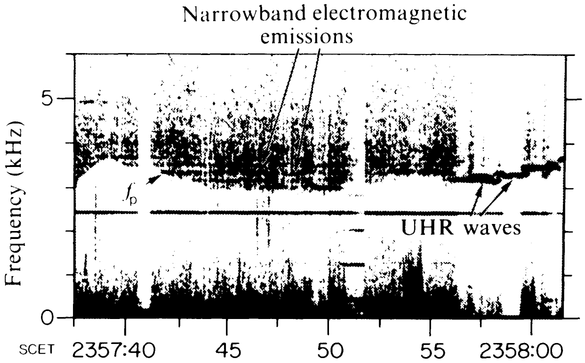


Fig. 6 A high-resolution spectrogram of narrowband electromagnetic emissions detected near the magnetopause during the Voyager 2 encounter 4 July 1979; $R = 71.5\ R_J$; $\lambda_m = 5.6°$; LT = 10.3 h. The UHR waves are electrostatic emissions generated near the upper hybrid resonance frequency, f_{UHR}. These emissions occur at discrete frequencies separated by the electron cyclotron frequency, $f_c = 28B$ Hz, where B is the magnetic field in nT.

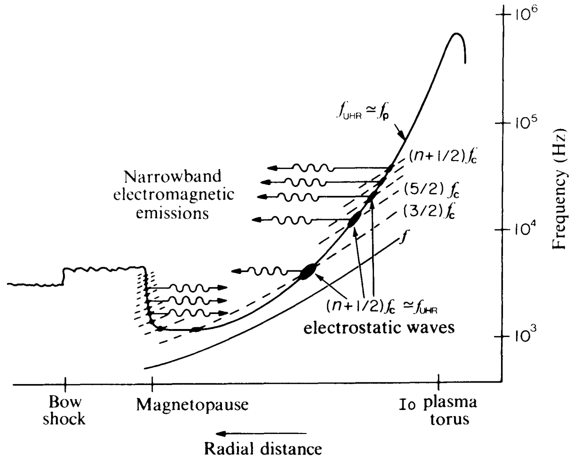


Fig. 7 A model illustrating a mechanism for generating the narrowband electromagnetic emissions in the jovian magnetosphere. An electron cyclotron instability is believed to produce electrostatic waves at $(n+1/2)f_c \simeq f_{UHR}$. These waves are then converted to electromagnetic radiation by a mode coupling process.

previously suggested[18,19]. The broadened width of the lines detected in the trapped continuum radiation (see Fig. 3) is believed to be due to fluctuations in the position of the magnetopause, which cause Doppler broadening as suggested by Barbosa[19]. If the emission frequency is above the magnetopause plasma frequency, then the radiation can propagate freely away from the planet.

The downward frequency drift for the event shown in Fig. 5 is strongly suggestive of a source moving outward away from the planet, emitting radiation near the local electron plasma frequency, similar to the mechanisms involved in Type II and Type III solar radio bursts. Based on the jovian electron density profile given by Gurnett *et al.*[20], the narrowband emissions in Fig. 5 would then be generated at radial distances of ~15–25 R_J, in the outer regions of the Io plasma torus. From the observed frequency drift rate the radial velocity of the source is estimated to be about $3R_J\ h^{-1}$ or $60\ km\ s^{-1}$. It is unlikely that the source motion could be produced directly by charged particles moving outward along the magnetic field lines comparable with Type III solar radio bursts, because the energies, 0.01 eV for an electron and 18 eV for a proton, are too small to produce plasma instabilities in the hot jovian plasma. More likely the source is associated with a cloud of plasma moving outwards through the magnetosphere near the equatorial plane. Interchange instabilities caused by the centrifugal force in the rapidly rotating magnetosphere of Jupiter are expected to cause radial transport of plasma outward from the Io plasma torus, perhaps producing isolated clouds of plasma moving outward through the magnetosphere. Isolated events of the type observed could be produced by temporal variations in the plasma source, possibly caused by changes in the volcanic activity of Io, which is the primary source of plasma in the jovian magnetosphere. Because the upper hybrid resonance instability is sensitive to the cold to hot plasma density ratio[12–15,21], a cloud of relatively cool plasma from the Io torus could trigger the upper hybrid resonance instability as it moved through the hot outer regions of the magnetosphere.

It is also possible that the radio emission could be associated with a transient cloud of plasma that is decaying in density at a fixed radial distance. In principle, a stationary decaying cloud can be distinguished from a moving cloud, because for a stationary cloud the frequency spacing, which is controlled by the magnetic field, should remain constant, whereas for a cloud moving radially outward the frequency spacing should decrease with increasing radial distance. In practice, because of the limited amount of wideband data available and the considerable complexity of the spectrum we are not able to distinguish these two possible interpretations.

Finally, we consider the possibility that the frequency drift could be caused by a frequency dependent latitudinal beaming of the radiation such as proposed by Jones[22] for the jovian kilometric radiation. In this case the frequency shift would be caused by the changing magnetic latitude of the spacecraft as the planet rotates. This beaming mechanism predicts both upwards and downwards frequency drifts depending on the phase of the planetary rotation. At present, no events with an upward frequency drift have been observed. Furthermore, according to Jones the frequency should increase with increasing latitude, opposite to the latitudinal variation evident for the event in Fig. 5. Thus, the latitudinal beaming model does not appear to provide a likely explanation for the observed frequency drift.

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