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Mode conversion at the Jovian plasma sheet boundary

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Abstract. The plasma wave data obtained by Galileo in Jupiter's magnetosphere often exhibit three distinct frequency bands in the frequency range between a few hertz and a few kilohertz. It is shown that these emissions are generally electromagnetic. They are identified by relating their characteristic frequencies to the solutions of the cold plasma dispersion relation. Four modes are possible: *X, Z, O,* and whistler. Knowing the electron gyrofrequency f_{ce} measured by the fluxgate magnetometer, we have considered two different hypotheses for the observed lower-frequency cutoff of the intermediate frequency emissions which occur below f_{ce}. Under these assumptions, characteristic frequencies have been computed from the cold plasma theory and compared with the set of cutoff frequencies derived from the observations. Consistency checks lead to the identification of the intermediate frequency band as being on *O* mode with a low-frequency cutoff at the electron plasma frequency f_p. Below the *O* mode, Galileo detects whistler mode emissions (below f_p). Above f_{ce} the observed emission is consistent with being *X* mode. An attempt is made to identify the source of the *O* mode radiation. Quasi-electrostatic waves are sometimes identified below the upper hybrid frequency when the plasma sheet boundary is crossed. We suggest that these electrostatic waves, which are presumably generated by field-aligned electron beams flowing along plasma sheet boundary, are successively mode converted into *Z* and later *O* mode. Thus the *O* mode observed mostly outside the plasma sheet is generated by mode conversion of primary electrostatic waves.

1. Introduction

The analysis of data from the Voyager plasma wave subsystem (PWS) obtained within Jupiter's magnetosphere has provided evidence for the presence of three bands of emissions covering a wide range of frequencies extending from a few hertz and to few kilohertz [*Gurnett et al.,* 1980] with an amplitude that remains about the same over a timescale of months [*Barbosa,* 1981]. Depending upon the location of Voyager, different plasma conditions have been encountered, leading to the identification of different modes. Low-frequency electromagnetic radiation, well below the electron gyrofrequency, has been detected in the lobes of Jupiter's magnetotail by *Moses et al.* [1987], who identified the low-frequency cutoff as the plasma frequency f_p, and they therefore conclude that the observed mode is *O* mode. The emission detected below f_p has been interpreted as being preferentially a *Z* mode radiation. Another class of emissions confined to the magnetic equator has been detected in the middle magnetosphere in a region where $f_p \geq f_{ce}$, by *Kennel et al.* [1987] and by *Barbosa et al.* [1990]. They have identified the observed intense narrowband emission as *Z* mode radiation, whereas the higher-frequency emission could be either *X* or *O* mode or a mixture of these two modes. During its orbital tour around Jupiter the Galileo spacecraft has carried out a more thorough investigation of the Jovian magnetosphere; furthermore, the PWS instrument on board Galileo provides better frequency resolution than Voyager and carries a search coil magnetometer, which allows a distinction to be made between electrostatic and electromagnetic modes [*Gurnett et al.,* 1992]. These new possibilities are used to further investigate the nature of the low-frequency radio emissions.

2. Observations

The Galileo trajectory in the Jovian environment consists of a series of elliptical orbits with an apoapsis between 70 and 150 Jovian radii (R_J) and a periapsis above 8 R_J during the nominal mission; it is located close to the geographic equatorial plane. Since the magnetic axis of Jupiter is not aligned with the geographic axis, Galileo covers a range of magnetic latitudes. Plate 1 presents a spectrogram of the waves detected up to 4 kHz, over almost two planetary rotations at a distance of about 45 R_J, at around 0030 local time and a magnetic latitude changing from 8° north to 11° south. The superimposed black line is the electron gyrofrequency f_{ce} deduced from the fluxgate magnetometer data; it exhibits large and relatively regular variations associated with Jupiter's rotation. When the magnetic field decreases sharply, Galileo is entering the plasma sheet; this sharp decrease occurs twice per rotation which is simply due to the fact that in a geographical frame the current sheet moves up and down, as the magnetic axis of Jupiter rotates around its geographic axis. At the same time as the magnetic field decreases, the density strongly increases, as is suggested by the large increase in the cutoff frequency of the highest-frequency band emission.

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In agreement with earlier observations made on Voyager, Galileo alternately detects three types of continuous radiation (see Plate 1). Let us focus, for example, on the period between 0500 and 0900 UT. Disregarding the spurious noise at 10 and 40 Hz, four types of emissions can be distinguished according to their frequency ranges. From the top to the bottom the highest-frequency emission above f_{ce} and up to ~ 2 kHz will be refered to as type A (before a precise identification); monochromatic emissions of short duration detected at f_{ce} at 0440, 0915 and 1915 UT are refered to as type B emissions. Below type A emissions, intense type C continuous emissions are observed with an upper cutoff at f_{ce}. Finally, below type C radiations, type D emissions are detected in the lowest part of the spectrogram; they extend up to about 200 Hz and are intense and continuous. Ten hours later, from 1500 to 1900 UT, very similar type A, B, C, and D emission patterns are again observed thereby illustrating the effect of Jupiter rotation at organizing these emission patterns. Emissions are also observed between 1100 and 1300 UT, half a Jovian rotation period later. In this case, however, the duration is shorter and the bandwith of these signals is narrower (types A and B are clearly identified during this period). Close examination over longer time periods (data not shown here) confirms that the emission patterns described above are regularly observed when Galileo is beyond 20 R_J. These patterns provide evidence for two sets of 10 hour periodicities. The asymmetry between the two sets of emissions, observed ~ 5 hours apart, is due to an asymmetry in the motion of Galileo with respect to the center of the plasma sheet. The frequency width of the spectra of types A, C, and D emissions depends upon the distance from Galileo to the boundary of the plasma sheet. A quasi-monochromatic emission (type B) is observed while Galileo remains close to the plasma sheet boundary. As Galileo gets farther away from the plasma sheet boundary, the spectrum extends toward lower and lower frequencies. In support of the interpretation that the breadth of the spectral band correlates with distance from the boundary, we notice that the time lag between crossings of the center of the plasma sheet (minimum of f_{ce}) is also asymmetric; this time lag is ~ 6 hours while the emissions are broadband and ~ 4 hours while they are narrower.

3. Interpretation

Let us now consider the case where Galileo is far from the plasma sheet and the types A, C, and D spectra are wider. We will start with the identification of these three types of signals: emissions A, C, and D. The spectrogram of the magnetic component, not shown here, has been used for determining whether these waves are electromagnetic or not. The three types of emissions A, C, and D are found to have a magnetic component as shown on the spectra of electric and magnetic components plotted on Figure 1. The ratios $\delta E/\delta B$ for the emissions A, C, and D are 5, 3.5, and 2.5 10^8 m/s, respectively, and are therefore of the order of the speed of light. Thus one can conclude that the three types of emissions are generally electromagnetic. The amplitude of the type C emission is predominant, and its amplitude is ~ 10^{-3} V/m. To identify the nature of these three emission bands, we use the same approach as *Kennel et al.* [1987], who fitted the observations with the solution of the cold plasma dispersion relation. We applied different interpretations of the lower cutoff of the type C emission band (below f_{ce}), then derived the other characteristic frequencies of the medium, and finally looked for consistency in the resulting type A emission band (above f_{ce}).

Knowing f_{ce}, four different characteristic frequencies remain to be determined. The whistler mode upper cutoff is the smaller of f_P and f_{ce}. The ordinary mode *O* lower cutoff is at the plasma frequency f_P. The extraordinary mode splits in two branches the *X* and *Z* modes, their lower cutoffs being at f_X and f_Z, respectively. The *Z* mode has a resonance at the upper hybrid frequency f_{UH}. These frequencies are linked to f_{ce} and f_p by the following relations:

$$f_P = \frac{Ne^2}{\varepsilon_0 m}; \quad f_{ce} = \frac{qB}{m}; \quad f_{UH}^2 = f_P^2 + f_{ce}^2$$

$$f_X = \frac{f_{ce}}{2} + \left(f_P^2 + \frac{f_{ce}^2}{4} \right)^{1/2}; \quad f_Z = -\frac{f_{ce}}{2} + \left(f_P^2 + \frac{f_{ce}^2}{4} \right)^{1/2}$$

where *N* is the plasma density and *B* the magnetic field intensity.

Let us assume first that type C emission is *O* mode; the lower cutoff should then be the plasma frequency. Then it is easy to derive the other characteristic frequencies which are plotted on Plate 2a. The same procedure has been applied after assuming that the type C emission is *Z* mode, as suggested by previous studies [*Kennel et al.*, 1987; *Barbosa et al.*, 1990]; then the lower cutoff should correspond to f_Z. The various characteristic frequencies corresponding to this hypothesis are plotted on Plate 2b. Type A emission could be either *X* or *O* mode with a cutoff at f_X or f_p. On Plate 2b the observed low-frequency cutoff of the type A emission is clearly below the computed f_X (triangles) and also well above f_p (diamonds). Conversely the observed type A cutoff matches pretty well the value of f_X displayed in Plate 2a. This leads us to conclude that the hypothesis made to create Plate 2a, namely, that type C is *O* mode emission, is correct. By the same token, type A is identified as *X* mode. If this interpretation is correct, type D should be whistler mode emission, and its upper frequency cutoff should be at f_P ($f_P < f_{ce}$). Thus the lower frequency cutoff of the type C (*O* mode) should coincide with the upper frequency cutoff of the type D (whistler mode); this is, indeed, what is observed; there is a minimum in the amplitude below f_P. A more precise determination of the frequency cutoffs can be obtained fom the spectra plotted in Figure 1.

Depending upon the location of the spacecraft with respect to the plasma sheet two complementary methods can be used. Outside of the plasma sheet the density is low ($f_P < f_{ce}$); the method described above gives the plasma frequency as the lower frequency cutoff of the intermediate frequency emission (type C identified as *O* mode). Inside the plasma sheet, for instance from 0900 to 1100 UT on Plate 1, the cutoff of type A emissions identified as *X* mode approaches f_P (since $f_P > f_{ce}$). The sharp transition from dark blue to green, for instance, from 0900 to 1100 UT, gives f_P in the high-density region. Thus one can successively use type A and type C cutoffs to determine f_P along the Galileo trajectory. A systematic study will be done elsewhere. Let us simply point out that this method (1) yields sharp density gradients at the

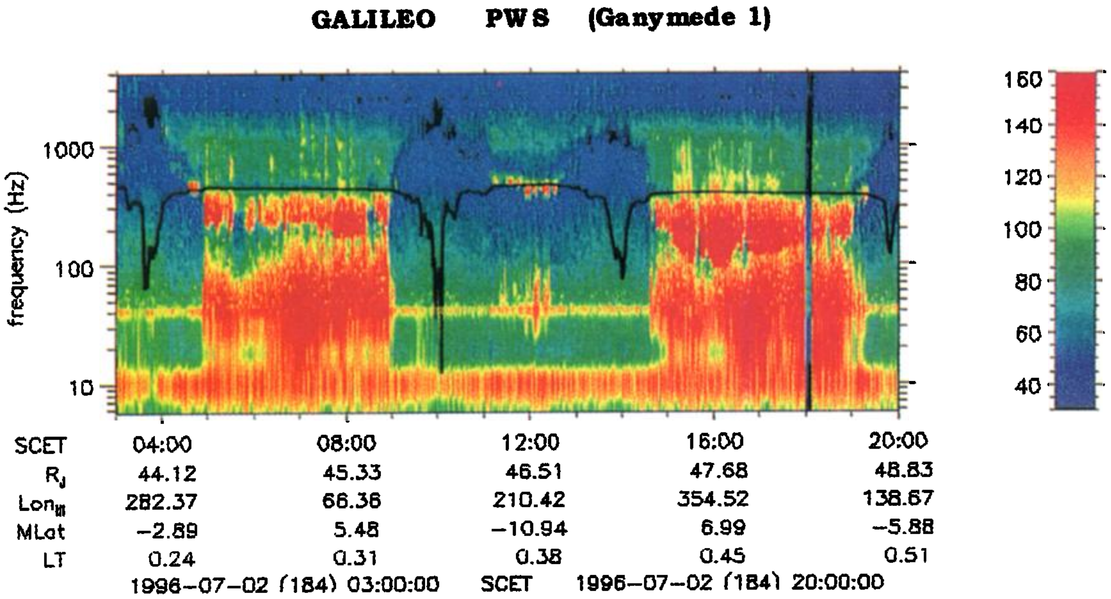
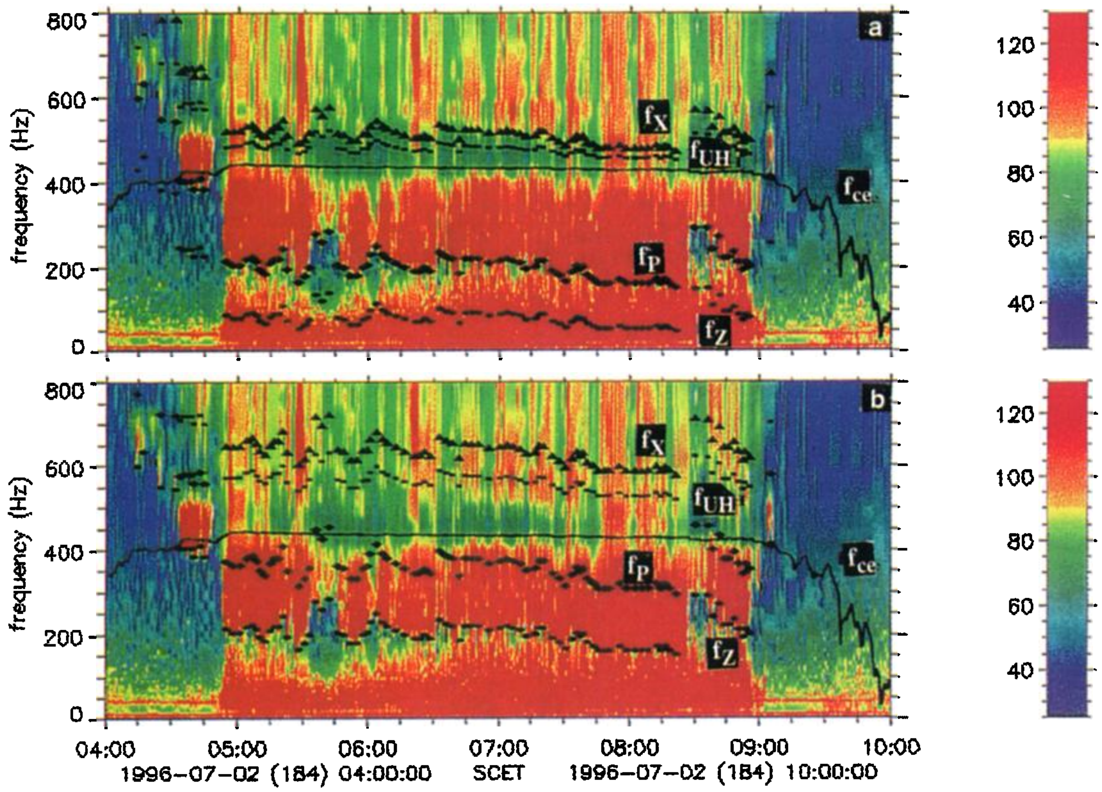
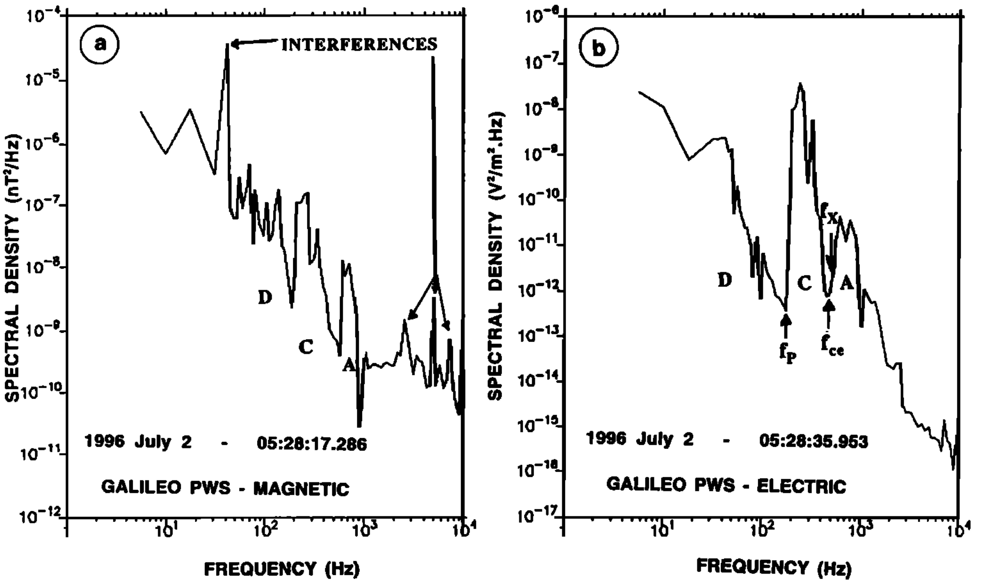


Plate 1. Frequency-time spectrogram of the electric field intensities detected by the Galileo plasma wave subsystem during the G1 orbit. The position of Galileo is given in system III, the distance is in Jovian radii. The black line superimposed on the spectrogram is the electron gyrofrequency computed from magnetometer data. The horizontal lines around 10 and 40 Hz are caused by spacecraft generated interference. The color scale shows the intensity in decibels.



Plates 2. Same as Plate 1 for a selected time interval from Plate 1. The curves identified with different markers correspond to the characteristic frequencies defined in the text. Two different assumptions (a) f_P or (b) f_Z have been made for the lower cutoff frequency (~200 Hz) of the intermediate frequency emission.



Figures 1. Spectra of the (a) magnetic and the (b) electric components taken almost at the same time (~ 18 s apart). The duration of the sweeps is 18 s. The intense emissions, labeled A, C, and D clearly have a magnetic component. The different cutoffs are identified in Figure 1.

plasma sheet boundary and (2) provides evidence for a plasma sheet which is much broader than the current sheet determined from the sharp decrease in the magnetic field.

4. Discussion

Similar observations, though with different plasma conditions, have been reported from Voyager 1 data. Both types of studies conclude that Z mode radiation exists. In the low plasma density found in the tail lobes, *Moses et al.* [1987] have identified *O* mode emission which concurs with our conclusion. For interpreting the emission occurring below f_p, two modes are possible: whistler or Z mode radiation. Moses et al. have eliminated the whistler modes because it requires electrons with a resonant energy greater than 25 MeV, which are unlikely to exist with a large enough density in the lobes. Taking advantage of the complete set of instruments onboard Galileo, we get a precise determination of the ratio: $\delta E/\delta B \sim 2.5\ 10^8$ m/s for the type D emission; we conclude that these emissions can be whistler mode in a low-density plasma. The resonant energy E_R can, indeed, be written [*Kennel and Petschek*,1966]:

$$E_R = \frac{1}{2} m V_R^2 = \frac{B^2}{8\pi N} \frac{f_{ce}}{f} \left(1 - \frac{f}{f_{ce}}\right)^3$$

with B=15.7 nT, f_{ce}=439 Hz, f_p~174 Hz, N~374 m^{-3}; for a maximum frequency of the spectrum at f~35 Hz, one gets electrons with an energy of 16 MeV which is about the same value as the one quoted by *Moses et al.* [1987] (25 MeV, see above). Yet the whistler mode is electromagnetic and can be observed at a large distance from its source. A large resonant energy is not therefore a sufficient reason to rule out the whistler mode. As a matter of fact, *Farrell et al.* [1993] have concluded that the electromagnetic waves that they observed at high magnetic latitudes during the Ulysses flyby of Jupiter is whistler mode emission generated along open field lines, possibly connected to the Jovian polar cusp. The whistler mode wave source identified by *Farrel et al.* [1993] may well be an adequate source for whistler mode waves observed at lower latitudes by Galileo.

Kennel et al. [1987] and *Barbosa et al.* [1990] have essentially observed a narrow band of Z mode radiation in high-plasma-density region in close vicinity of the plasma sheet. One reason that Barbosa et al. confined themselves to studying a regime where $f_p > f_{ce}$ is instrumental; the Voyager wideband data were usually processed with a spectral resolution of about 28 Hz, limited by the duration of consecutive samples (55.5 ms). When f_p was very low, much lower than f_{ce}, the spectral resolution was not sufficient to study cutoffs and resonances with reasonable accuracy. Furthermore, the low-frequency continuum was so intense that it determined the gain of the automatic gain control, making weaker features almost impossible to detect. Thus Kennel et al. and Barbosa et al. had to concentrate on regions of high-frequency emissions (around or above f_{ce}), whereas our study is focused at higher distances from the plasma sheet where the frequency is below f_{ce} and where the corresponding radiations are identified as *O* mode emissions.

What is the origin of type *C*/*O* mode emissions? As indicated above, there is a sharp increase of f_p at the edges of the plasma sheet, where *O* mode emissions cut off. This provides evidence for a sharp density gradient directed toward the center of the plasma sheet. The magnetic field gradient is oppositely directed, and this gradient is sharp near the plasma sheet center (current sheet). Near the plasma sheet boundary, f_p matches f_{ce} and on some occasions intense type B, narrowband emissions are observed for $f \sim f_{ce}$. This is the case, for instance, between t=0430 and t=0450 UT on Plate 2. We have not found any of these bursty monochromatic emissions of brief duration with a magnetic component. Therefore we consider these waves to be electrostatic. They correspond probably to the Z radiation reported by *Kennel et al.* [1987] and *Barbosa et al.* [1990]. These electrostatic emissions could result from the interaction with parallel electron beams flowing along the boundary of the plasma sheet toward or away from the planet. The emitted frequency f_0 is located in a very limited frequency range, between f_p or f_{ce} (whatever is the larger) and f_{UH} which could reach a maximum value: $\sqrt{2} f_p$, if $f_{ce}=f_p$. Given that the magnetic field is essentially along the plasma sheet boundary and that the density and magnetic field gradients are essentially perpendicular to it, one can assume that the medium is stratified in a direction perpendicular to the magnetic field. Thus, as the waves propapagate, $k_{//}$ is essentially constant, and $k_\perp$ varies, which makes it possible to use the classical techniques developed for stratified media. As they propagate toward the center of the plasma sheet, quasi-electrostatic waves become electromagnetic Z mode. *Budden* [1985] has studied the propagation of radio waves in a stratified medium (the Earth ionosphere), and we have based our analysis on his results. For sake of simplification we have assumed that f_p is equal to f_{ce} in the region of generation; thus $0.5<X<1$ and $Y<1$ where

$$X = \frac{f_P^2}{f^2} \text{ and } Y = \frac{f_{ce}}{f}.$$

We have used the refractive index surfaces computed by Budden for the extraordinary mode for $Y=0.5$ and for $X>1-Y^2$ [see *Budden*, 1985, p. 269]. The case $Y=0.5$ has been chosen since when the conversion mechanism is operating, the type B/Z wave has propagated deep into the plasma sheet, in a region where f_{ce} has decreased compared with its value in the source region of the Z mode.

The refractive index surfaces for the extraordinary mode, displayed in Figure 2, have been adapted from *Budden* [1985], for the case where the magnetic field direction is perpendicular to the gradient (essentially the density gradient). For $X=1$ the refractive index is equal to unity; this occurs along a fraction of the horizontal axis (P_1P and QQ_1) along the direction of the magnetic field and along the unit circle (labeled $X=1$ in figure 2). The points P and Q are also part of the refractive index of the O mode; thus mode conversion will take place whenever the ray path is such that P or Q are crossed. As indicated above, $k_{//}$ and therefore $n_{//} = k_{//}c/\omega$ is conserved. Conversely, $k_\perp$ and $n_\perp$ change; the variations of $n_\perp$ are given by the straight lines perpendicular to the magnetic field (i.e., along z axis) in Figure 2. As the ray moves (downward) toward the plasma sheet, $n_\perp$ decreases and $n_{//}$ is conserved; the primary electrostatic wave with a large $k_\perp$ becomes a Z mode (representative points: 1, 2, and 3 in Figure 2). At point 4 the group velocity, indicated by thick arrows, is along B_0, and therefore the ray path which was moving toward the center of the plasma sheet is reflected, as sketched in the left-hand side of Figure 2, above the level X-$Y=1$ ($X=1.5$ in this case) corresponding to the cutoff of the Z mode. Depending upon the initial value of $n_{//}$, two cases are possible. If the vertical line (right-hand side of Figure 2) crosses the horizontal axis at point P or Q, then the mode converts from Z to O mode. This O mode afterward propagates away from the plasma sheet and can freely escape, as sketched by a shaded line in the left-hand side of Figure 2. Conversely, if the vertical solid line (right-

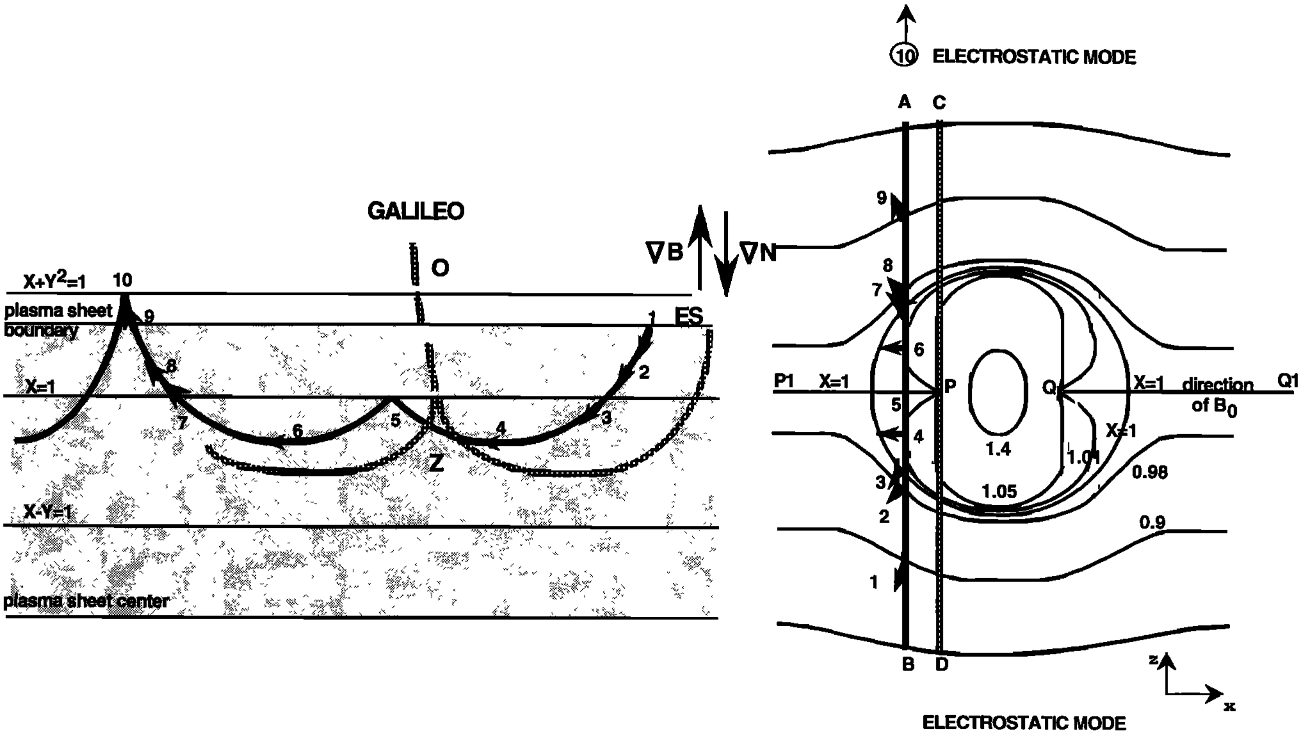


Figure 2. (left) Cross section in the magnetic meridian plane of the refractive index surfaces for the Z mode when $Y=1/2$. The numbers by the curves are the values of X [from *Budden*, 1985]. The magnetic field is along the x axis, and the density and magnetic gradients are antiparallel and aligned with the z axis. (right) The two vertical lines, AB and CD, indicate the loci of the refractive index ($n_{//}$ is constant). The thick arrows give the direction of the ray, perpendicular to the refractive index surfaces. The ray trajectories corresponding to the two vertical lines are shown on the left-hand side.

hand side of Figure 2) crosses the horizontal axis beyond *P* or *Q*, the ray is reflected (point 5); most of the energy remains in the *Z* mode, and the same process repeats; the *Z* mode reflects again (point 6), becomes again electrostatic, and reflects before or when the frequency matches the upper hybrid frequency (point 10 at the level $X+Y^2=1$). The ray path is trapped in a thin region, the edge of the plasma sheet, until its representative point in the right-hand side of Figure 2 gets close to *P* or *Q*, where it mode converts into an escaping *O* mode (as discussed above). The efficiency of the conversion depends upon the direction of the wave normal (see the theory of radio windows given by *Budden* [1980].

The origin of the type A/*X* mode emission is likely to be the cycloton maser instability which could be generated at long distance [*Ladreiter and Leblanc*, 1990]. From the frequency of the emission ($f_A \sim$ 800 Hz for this event) detected by Galileo and a magnetic field model, it is possible to localize the region where this mechanism takes place ($f_{ce} \sim f_A$); we do not analyze further here the origin of these *X* mode emissions.

5. Conclusion

Three types of electromagnetic radiation are commonly observed when Galileo leaves the central plasma sheet. Detailed comparison between cutoff and solution of the dispersion relation has allowed us to identify these modes as whistler mode waves in a regime where $f_p < f_{ce}$, *O* mode ($f_p < f \leq f_{ce}$), and *X* mode ($f > f_X$). The origin of the observed *O* mode has been investigated. It has been shown to be generated by electrostatic waves/*Z* mode generated close to the plasma sheet boundary. As the distance between Galileo and the plasma sheet increases, *O* mode waves generated by the same process at larger distances from Jupiter can be observed as long as their frequency is above the local *O* mode cutoff, f_p. Then the local value of f_p determines the "line of horizon". As Galileo gets farther away from the plasma sheet, f_p decreases, and remote sources at larger distances (smaller frequencies) become observable thereby allowing a remote sensing of distant radio sources.

The linear conversion, in concentration gradients, of electrostatic upper hybrid emissions via the *Z* mode to escaping electromagnetic ordinary *O* mode waves has been invoked as the source of terrestrial myriametric and Jovian kilometric radiation in a situation where $f_p > f_{ce}$ [*Jones*, 1980]. The limited dimensions of the radio windows make it an inefficient avenue for mode conversion [*Barbosa*, 1982]. The dimensions of the radio windows have been revisited by *Budden and Jones* [1986] who found a larger conversion coefficient than the one obtained in earlier works. We are not aware of any detailed estimate of the efficiency of the conversion for $f_p < f_{ce}$ applicable in the present case.

Future work will be developed along three lines: (1) estimation of conversion efficiency, which requires detailed modeling of gradients, (2) modeling of the plasma sheet density to complement magnetic field models, and (3) generation of type D/whistler mode and A/*X* mode.

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References

Barbosa, D. D., Fermi-Compton scattering due to magnetopause surface fluctuations in Jupiter's magnetopshere cavity, *Astrophys. J., 243,* 1076, 1981.

Barbosa, D. D., Low level VLF and LF radio emissions observed at Earth and Jupiter, *Rev. Geophys., 20,* 316, 1982.

Barbosa, D. D., W. S. Kurth, S. L. Moses, and F.L. Scarf, *Z* mode radiation in Jupiter's magnetopshere: The source of Jovian continuum radiation, *J. Geophys. Res, 95,* 8187, 1990.

Budden, K. G., The theory of radio windows in the ionosphere and magnetosphere, *J. Atmos. Terr. Phys., 42,* 287, 1980.

Budden, K. G., *The Propagation of Radio Waves,* Cambridge Univ. Press, New York, 1985.

Budden, K. G., and D. Jones, Full wave calculations of radio windows and their relevance to the theory of production of planetary non-thermal continuum radiation, *Comparative Study of Magnetospheric System,* pp. 563-580, Centre National d'Etudes Spatiales, Cepadeus-Ed., Toulouse, France, 1986.

Farrell, W. M., et al., Ulysses observations of auroral hiss at high jovian latitudes, *Geophys. Res. Lett, 20,* 2259, 1993.

Gurnett, D. A., W. S. Kurth, and F. L. Scarf, The structure of the Jovian magnetotail from plasma wave observations, *Geophys. Res. Lett., 7,* 553, 1980.

Gurnett, D. A., W. S. Kurth, R. R. Shaw, A. Roux, R. Gendrin, C. F. Kennel, F. L. Scarf and S. D. Shawhan, The Galileo plasma wave investigation, *Space Sci. Rev., 60,* 341, 1992.

Jones, D., Latitudinal beaming of planetary radio emissions, *Nature, 288,* 255, 1980.

Kennel, C. F., and H. E. Petschek, Limit on stably trapped particle fluxes, *J. Geophys. Res., 71,* 1, 1966.

Kennel, C. F., R. F. Chen, S. L. Moses, W. S. Kurth, F. V. Coroniti, F. L. Scarf, and F. F. Chen, *Z* mode radiation in Jupiter's magnetosphere, *J. Geophys. Res., 92,* 9978, 1987.

Ladreiter, H. P., and Y. Leblanc, Source location of the Jovian hectometric radiation via ray tracing technique, *J. Geophys. Res., 95,* 6423, 1990.

Moses, S. L., W. S. Kurth, C. F. Kennel, F. V. Coroniti, and F. L. Scarf, Polarization of low-frequency electromagnetic radiation in the lobes of Jupiter's magnetotail, *J. Geophys. Res., 92,* 4701, 1987.

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