

Radio emission observed by Galileo in the inner Jovian magnetosphere during orbit A-34

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Abstract

The Galileo spacecraft encountered the inner magnetosphere of Jupiter on its way to a flyby of Amalthea on November 5, 2002. During this encounter, the spacecraft observed distinct spin modulation of plasma wave emissions. The modulations occurred in the frequency range from a few hundred hertz to a few hundred kilohertz and probably include at least two distinct wave modes. Assuming transverse EM radiation, we have used the swept-frequency receivers of the electric dipole antenna to determine the direction to the source of these emissions. Additionally, with knowledge of the magnetic field some constraints are placed on the wave mode of the emission based on a comparative analysis of the wave power versus spin phase of the different emissions. The emission appears in several bands separated by attenuation lanes. The analysis indicates that the lanes are probably due to blockage of the freely propagating emission by high density regions of the Io torus near the magnetic equator. Radio emission at lower frequencies (< 40 kHz) appears to emanate from sources at high latitude and is not attenuated. Emission at $f > 80$ kHz is consistent with O-mode and Z-mode. Lower frequency emissions could be a mixture of O-mode, Z-mode and whistler mode. Emission for $f < 5$ kHz shows bands that are similar to upper hybrid resonance bands observed near the terrestrial plasmopause, and also elsewhere in Jovian magnetosphere. Based on the observations and knowledge of similar terrestrial emissions, we hypothesize that radio emission results from mode conversion near the strong density gradient of the inner radius of the cold plasma torus, similar to the generation of nKOM and continuum emission observed in the outer Jovian magnetosphere and in the terrestrial magnetosphere from source regions near the plasmopause.

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1. Introduction

On November 5, 2002, the Galileo spacecraft made a pass in to a radial distance of $1.98 R_J$ (Jovian radii) from Jupiter, much closer than on any previous orbit. Data were successfully acquired during the entire inbound pass through the hot and cold plasma torii, and through the region inside the cold torus to a radial distance of $2.32 R_J$, at which point the data system went into safing due to the intense radiation in the inner region of the magnetosphere.

For this pass, the spacecraft passed through the cold plasma torus and into the region between Jupiter and the Io torus. In this previously unexplored region, the plasma wave observations show an array of emission and attenuation bands that are not totally understood. These bands were observed again, with some modifications, during the final Galileo trajectory orbit 35, that ended with the spacecraft plunging into the Jovian atmosphere.

Pertinent to the observations of Galileo are past Voyager and Ulysses observations of radio emission. Jovian narrowband kilometric (nKOM) radio emission was first reported from the Voyager radio emission data (Warwick et al., 1979a, b; Kaiser and Desch, 1980). The emission is characterized by its obvious narrow band

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(~ 50 kHz) and its relatively smooth morphology. Daigne and Leblanc (1986) reported the emission to be LH polarized when observed by Voyager from the northern magnetic hemisphere and RH polarized when observed from the southern. Thus it is consistent with O-mode emission and may be related to terrestrial continuum emission (Gurnett, 1975). A number of theoretical models for the generation nKOM currently exist (cf. Jones, 1987, 1988; Fung and Papadopoulos, 1987). The interesting aspect of the Voyager observations of nKOM was that it appeared to recur at intervals that lagged the system III longitude by about 3–5%. The source was thus thought to be in the outer regions of the Io torus at about 8 or 9 R_J . The Ulysses observations of nKOM were well presented by Reiner et al. (1993) using the unique direction finding characteristics of the Unified Radio and Plasma Wave (URAP) experiment. The results rather surprisingly indicated that the nKOM originates from a number of distinct sources located at different Jovian longitudes and at the inner and outermost regions of the Io plasma torus. While both RH and LH polarization was observed, the results from sources in the outermost torus seem to favor the X-mode.

Jovian broadband kilometric emission (bKOM) was discovered by Voyagers 1 and 2 in the frequency range from sometimes as low as 30 kHz to typically several hundred kilohertz (but sometimes extending to ~ 1 MHz) (Warwick et al., 1979a, b). Green and Gurnett (1980) have conducted ray tracing studies of the emission and shown that it is consistent with a source region along auroral field lines between the Io torus and the Jovian ionosphere. One effect of the Io torus on L–O-mode emission from a source near Jupiter is to refract the rays away from the magnetic equator forming a shadow zone at radial distances beyond the torus. The emission shows a periodicity relative to Jovian system III longitude with a main component displaying right-hand polarization when observed in the range $140^\circ < \lambda_{III} < 240^\circ$ and left-hand polarization elsewhere (Leblanc and Daigne, 1985). More recently, Reiner et al. (1994), using Ulysses data from the URAP radio receiver, have identified a new component of bKOM referred to as sKOM or smooth kilometric radiation. This is a weaker emission (~ 100 times weaker than bKOM) and is observed in the range $120^\circ < \lambda_{III} < 230^\circ$ where bKOM is often absent. It was observed by URAP when Ulysses was at large southern Jovian latitudes. The source of the emission near a frequency of 100 kHz was determined to be about 4.5 R_J from Jupiter at a latitude of about 35°S. The polarization is consistent with O-mode emission.

Kaiser et al. (1993) discuss what was then a new radio source of ordinary and Z-mode emissions from the Jovian polar region. The observations were obtained when Ulysses was near closest approach and highest latitude on February 8, 1992. The emission lies in the

frequency range from about 5 kHz $< f < 50$ kHz with a peak intensity near 17 kHz, and the source region appears to be centered near system III longitude, $\lambda_{III} = 208^\circ$ at a distance of nearly 4 R_J from the planet. The best-fit source location occurs for a point at Jovigraphic latitude of 51° and $r = 3.8 R_J$ from the planet, in the vicinity of the north dipole axis. The source is at a high L-shell of approximately $L = 16$, and the intersection of this field line with the Jovian cloud tops is at about 65° Jovigraphic latitude in the range $195^\circ < \lambda_{III} < 200^\circ$. The depth of the spin modulation studies suggest the source is about 1 R_J in extent. It is also most interesting to note that Ulysses did not observe this emission from the southern hemisphere even though the viewing latitude should have been favorable for conjugate emission.

In this paper we examine in some detail the radio emission data obtained by Galileo in the inner Jovian magnetosphere during orbit A-34, and attempt to determine the mode and source of the emission, particularly in light of the Ulysses observations of ordinary and Z-mode emissions.

2. Galileo observations

As on previous passes through the Io plasma torus a narrowband electrostatic emission at the upper hybrid resonance frequency provided a very accurate measurement of the electron density (Gurnett et al., 2001). In Fig. 1 we show a frequency–time spectrogram of the plasma wave electric field intensity for a 3.7 h period on day 309 of 2002 from 03:00 to 06:40 (all time units are in UT). The upper hybrid resonance frequency, f_{UH} , the electron cyclotron frequency, f_c , and the hydrogen cyclotron frequency, f_H , are indicated by white lines for periods when the spacecraft was in the warm and then cold torus. The interpretation of the dark line will be discussed later (Fig. 6). The peak electron density, $2.6 \times 10^3 \text{ cm}^{-3}$, occurs just before the inner edge of the hot torus, which is at about 5.62 R_J (03:17:30). As the spacecraft enters the cold torus the electron density drops to about $6.0 \times 10^2 \text{ cm}^{-3}$ and then gradually increases as the spacecraft approaches Jupiter, reaching a peak of about $2.5 \times 10^3 \text{ cm}^{-3}$ at 4.86 R_J (04:02:15), shortly before the inner edge of the cold torus. At the inner edge of the cold torus, which occurs at 4.76 R_J (04:08:00), the electron density drops dramatically to levels on the order of 1 cm^{-3} . The electron density in this inner region is difficult to interpret because the upper hybrid emission can no longer be clearly identified, and there are numerous narrowband emissions with cutoffs that may or may not be associated with the local electron plasma frequency. As in the warm torus, the low density region inside the cold torus has a persistent level of plasma wave noise below about 10^3 Hz that is tentatively interpreted as whistler mode

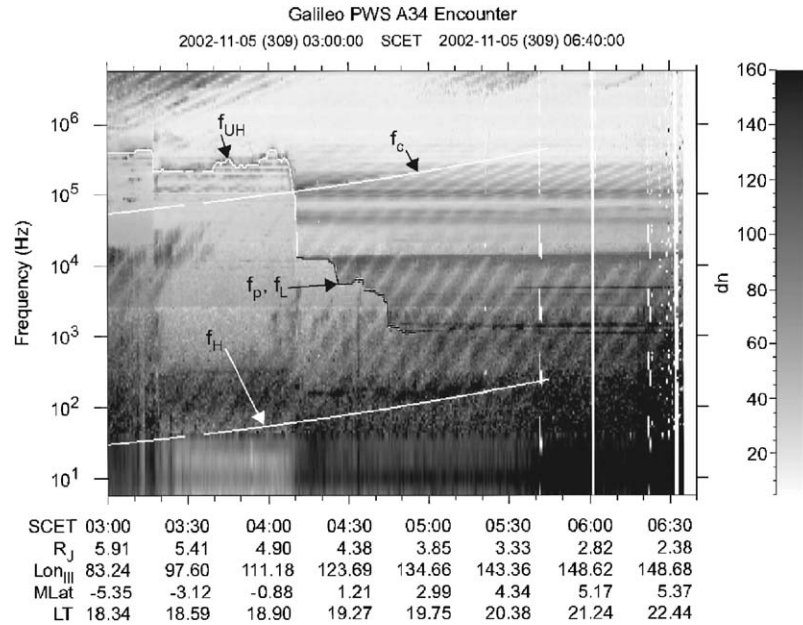


Fig. 1. Frequency–time spectrogram of the plasma wave electric field intensity for a 3.7h period on day 309 of 2002 from 03:00 to 06:40. The frequency range is from 5.6Hz to 5.6MHz. The upper hybrid resonance frequency, f_{UH} , electron cyclotron frequency, f_c , and ion cyclotron frequency, f_H , are indicated with a white line for periods when the spacecraft was in the warm and then cold torus.

noise (see Fig. 1). The intensity of the whistler mode noise increases noticeably as the spacecraft crosses Thebe’s orbit at $3.1 R_J$ (05:43:30), and increases markedly as the spacecraft crosses Amalthea’s orbit at $2.6 R_J$ (06:14:30). The wideband waveform data show numerous discrete emission bands $f < 5$ kHz.

3. Direction finding

Direction finding of radio emission observed by Galileo using spin modulation has been described in the past (cf. Menietti et al., 1998). The Galileo plasma wave instrument (PWS) has a single electric dipole antenna along the spacecraft x -axis. A freely propagating electromagnetic wave will be received with maximum intensity if the antenna is perpendicular to the wave vector of the incoming wave. This allows a determination of the direction to the source region in the spin-plane of the spacecraft (x – y plane). In other words, we determine the plane containing the source and the spin axis of the spacecraft. The depth of the emission nulls, along with some information about the source size, provides an estimate of the extent of the source region in the plane perpendicular to the spin plane (cf. Fainberg et al., 1972).

The spacecraft will be in a good orientation for direction finding if the spacecraft spin axis is perpendicular to the source direction. Since the spacecraft spin axis points essentially at the Earth, Galileo is in a favorable position to see spin modulation for local times centered near 6 and 18 h. The modulation of the wave

intensity is produced by a “beating” of the PWS frequency cycling period (18.67 s) against the spin period of the spacecraft (~ 19.0 s). The modulation disappears if the source signal strength decreases or if the spacecraft orientation relative to the source is not favorable.

For the emission seen in Fig. 1 spin modulation occurs for most of the emission observed when the spacecraft was within the inner radius of the cold plasma torus ($t > 04:10$ UT). We call this region the Jovian inner region (JIR). Note that the emission seems to occur in bands and that the pattern of spin modulation is not always the same in each band. This is an indication that the direction to the source has changed. In Fig. 2 we display results of direction finding for a number of frequencies. The directions are plotted in the spin plane of the satellite, when the Galileo spacecraft was within the JIR after a spacecraft event time of 04:30. The direction finding calculations were performed for 11 frequencies ranging from 563 Hz to 252 kHz for data extending in time from about 04:40 to 06:00. Superimposed on this plot are contours of the electron plasma density of the Io plasma torus as determined from the Divine and Garrett model (1983), to give an indication of the location of the regions of dense plasma. We also plot contours of f_c for several frequencies. The interesting result is that the emission appears to have two distinct source regions, one at low latitude near the plasma torus central density peak, and the other at high latitude. We note that the method of direction finding based on spin modulation produces a result with a 180° ambiguity. We have assumed the low-latitude emission has a source in the direction of the Io torus. The Io torus

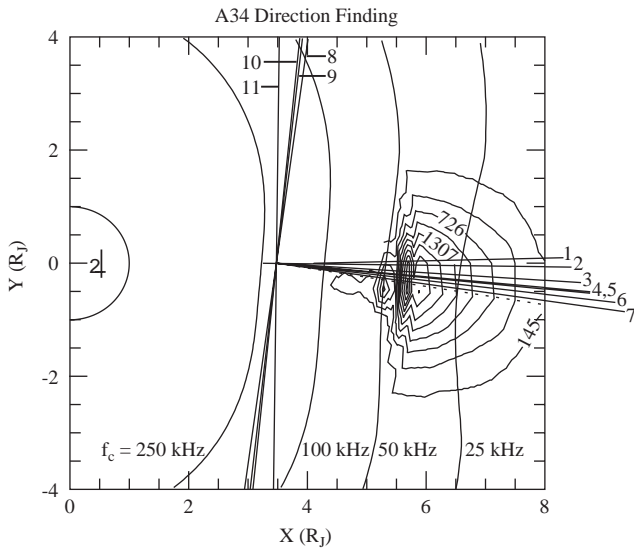


Fig. 2. Results of direction finding for a number of frequencies. The directions are plotted in the spin plane of the satellite. Superimposed on this plot are contours of model electron plasma density of the Io plasma torus. The dotted line indicates the direction for the “leaking emission” at 25.1 kHz. Also plotted are contours of f_c for several frequencies. The direction frequencies are identified as (1) 252 kHz, (2) 250 kHz, (3) 164 kHz, (4) 126 kHz, (5) 139 kHz, (6) 101 kHz, (7) 113 kHz, (8) 50 kHz, (9) 46 kHz, (10) 563 Hz, and (11) 6.7 kHz.

is a rich source of radio emission with many terrestrial analogies as we discuss later. The high-latitude sources could be from either or both Jovian hemispheres.

The emission in Fig. 1 shows two attenuation lanes, in the frequency range from ~ 65 to ~ 80 kHz, and the second in the range ~ 15 to ~ 35 kHz. The emission for $f > 80$ kHz (above the attenuation lane at highest frequency) has a source near the center of the plasma torus. The directions are indicated for frequencies of 100.8, 113.4, 126.0, 138.6, 163.8, and 252.0 kHz. The emission at almost all lower frequencies appears to have a source at high latitude. The directions are indicated for frequencies of 0.563, 6.69, 45.6, and 49.5 kHz. For the second attenuation lane, we see that some emission appears to “leak” into the lane and become more intense for later times and changing system III longitudes. This leaking emission appears to have a source at low latitude, just as the emission for $f > 80$ kHz. The propagation direction for “leaking” emission at a frequency of 25.1 kHz (within the second attenuation lane) is indicated in Fig. 2 by the dotted line. The remaining emission for $f < 65$ kHz has a high-latitude source.

For directional information out of the spin plane we have calculated the modulation index, M , which is essentially a measure of the depth of the nulls (valleys) of the modulated signals relative to the background signal (cf. Fainberg et al., 1972). If we assume that the source is a point source out of the spin plane, it can be

Table 1
Out of spin plane angle

f (kHz)	θ (degs.)
25.1	57.3
100.8	26.5
113.4	17.9
126.0	25.7
138.6	17.4
163.8	32.8
252.0	26.7
0.563 ^a	20.3
6.69 ^a	26.1
45.6 ^a	47.5
49.5 ^a	34.9

^aHigh-latitude source.

shown that $\cos \theta = \sqrt{2M/(1+M)}$, where θ is the latitudinal angle measured from the spin plane to the source. In Table 1 we list the angles θ for each of the frequencies calculated. Note that the values for the low-latitude sources range from 17.4° to 32.8° except for the “leaking emission” at 25.1 kHz, which has a relatively large out-of-plane angle of 57.3° . The high-latitude sources have a similar range of angles. We do not believe that the shift in the spin modulation results (from low-latitude to high-latitude sources) is due to a “halo-like” source distribution as described by Reiner and Stone (1990). These authors have shown that the antenna response of a spinning dipole to such a distribution of scattering sources located in an annular ring, perpendicular to the spin plane of the dipole, can produce an artificial shift of the apparent source direction by 90° under some conditions. One important indication that this effect is present is that the modulation index goes to zero or a minimum value near the frequency at which the apparent source direction changes dramatically. Looking at Table 1 we see that there is no such variation of the modulation index for our results. Also, the halo effect is derived for the case of the satellite spin axis perpendicular to the plane of the halo. For Galileo, the satellite spin axis is in the plane of the torus. The emission from the torus is also not characterized as smooth or homogeneous as are the scattering sources of the halo distribution, rather, the torus emissions as well as auroral emissions such as bKOM are usually confined in source size and have significant temporal changes.

4. E vs. B

The ambient magnetic field, B , along the spacecraft trajectory in the near Jupiter region is nearly perpendicular to the orbital plane of Galileo. Since we are assuming that the emission is freely propagating with the wave vector perpendicular to the plane of the electric

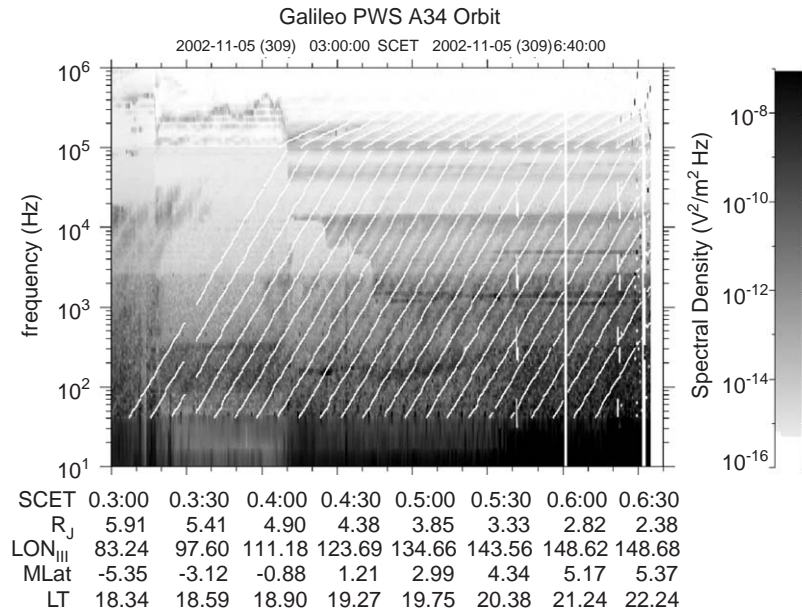


Fig. 3. The times when the angle between the oscillating electric field and the ambient magnetic field is near 90° , overplotted in white. For times $t > 05:44:47$, due to an absence of data, a model ambient magnetic field was used. For $f > 80$ kHz, the white lines lie near the emission nulls, implying a propagation of radio emission nearly perpendicular to B . For emission at almost all lower frequencies the white lines fall near the emission peak center, implying radio propagation at high latitudes.

field, we have calculated the angle between the oscillating electric field and the ambient magnetic field. In Fig. 3 we have overplotted in white the times when this angle is near 90° . For times, $t > 05:44:47$ due to an absence of data, a model ambient magnetic field is used (Connerney et al., 1998), but this field is probably quite accurate for the inner Jovian magnetosphere. From this plot it is seen that for the emission with $f > 80$ kHz the white lines lie near the modulating emission nulls, implying a propagation of radio emission nearly perpendicular to B (and thus with a source at low latitude). For emission at almost all lower frequencies the white lines fall near the modulating emission peaks, implying radio propagation nearly parallel to B , and thus with a source at high latitudes, consistent with the direction finding results. The only exception is the emission that appears to “leak” into the emission band in the frequency range from about 15 to 35 kHz. This emission appears to be coming from a low-latitude source region.

We further analyze emission at a number of frequencies in order to better identify the wave mode or possible source region. In Fig. 4, for $f = 201.6$ kHz, we display a polar plot of the electric field spectral density (radius) versus the angle, β , of the electric field antenna with respect to the local ambient magnetic field. At $t = 04:52:25$ the local cyclotron frequency is near 202 kHz. All the points on Fig. 4 for which the electric field spectral density is larger than 1.0×10^{-15} ($V^2 m^{-2} Hz^{-1}$) occur for times less than 04:52:25, and the range of the angle β is $52.4^\circ < \beta < 129.3^\circ$. It is clear from the figure that, for $t < 04:52:25$, the largest electric

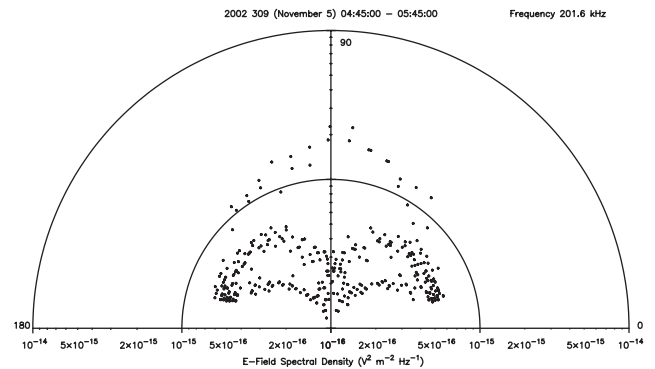


Fig. 4. Polar plot of the electric field spectral density (radius) versus the angle, β , of the electric field antenna with respect to the local ambient magnetic field for $f = 201.6$ kHz. At $t = \tau = 04:52:25$ the local cyclotron frequency is near 202 kHz. For $t < \tau$, the largest electric field spectral density of the emission is predominantly perpendicular to B , while for $t > \tau$, the largest electric field spectral density is predominantly parallel to B , indicating a distinct mode change.

field spectral density of the emission is predominantly perpendicular to B , consistent with upper hybrid electrostatic emission or with X- or Z-mode electromagnetic emission. For $t > 04:52:25$, the largest electric field spectral density is predominantly parallel to B , indicating a distinct mode change, consistent with propagating electromagnetic emission, perhaps O-mode. With only a single dipole antenna, no definitive polarization identification is possible from PWS.

In Fig. 5a we plot the electric field spectral density versus time for the frequency of 252.0 kHz. Clearly seen is the spin modulation. At 05:08 the local cyclotron

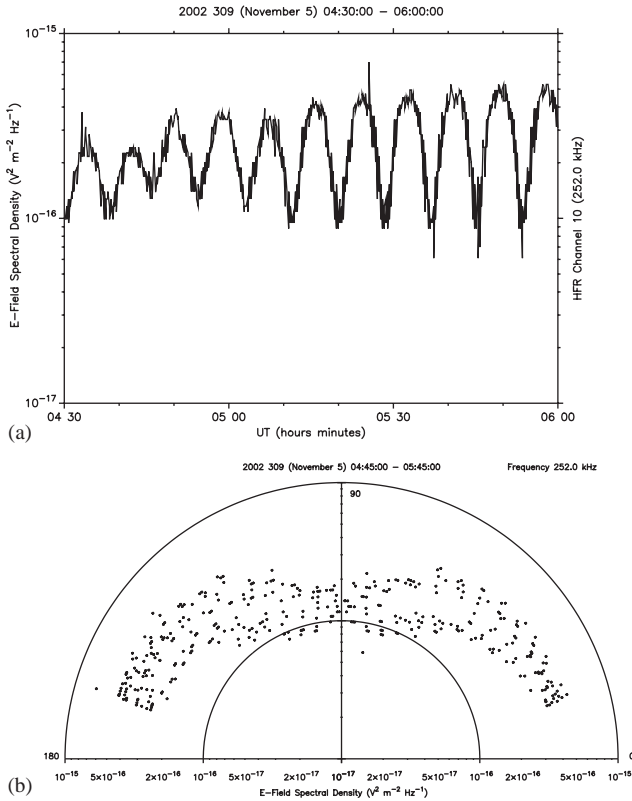


Fig. 5. (a) Intensity of the electric field versus time for the frequency of 252 kHz. Clearly seen is the spin modulation. At 05:08 the local cyclotron frequency is also about 252 kHz. There is no significant change in the spin modulation phase indicating that this emission is independent of magnetic field, as would be the case for O-mode emission. (b) Polar plot of the electric field shown in the same format as Fig. 4. There is no quantitative change in the electric field spectral density for data for $t < 05:08$ compared to data for $t > 05:08$.

frequency is also about 252 kHz. Note that there is no significant change in the spin modulation phase indicating that this emission is independent of magnetic field, as would be the case for L–O-mode emission. Fig. 5b shows the polar plot of the electric field for this frequency in the same format as Fig. 4. There is no quantitative change in the electric field spectral density for $t < 05:08$ compared to $t > 05:08$. The plot shows that the smallest spectral densities occur for angles β close to 90° , but there are not two distinct groupings of spectral density as we saw in Fig. 4. This indicates that the emission at 252 kHz did not undergo any significant mode change as was observed for the emission at 201.6 kHz.

5. Wideband data

In Fig. 6 we show a plot of the high-resolution data from the wideband instrument on board Galileo. This instrument was in a mode to monitor frequencies less than 10 kHz at the time. In this plot we observe what appears to be a cutoff, which is shown as a dark line, f_{cutoff} . This cutoff is consistent with two interpretations. One is that it corresponds to f_p , the plasma frequency, in which case all emission for $f < f_p$ would exclude O-mode emission, and whistler mode emission is excluded for $f > f_p$ (since $f_c \gg f_p$). The other interpretation is that the cutoff corresponds to f_L , where $f_L = -f_c/2 + \sqrt{(f_c/2)^2 + f_p^2}$ (Stix, 1992) in which case Z-mode is excluded for $f < f_L$.

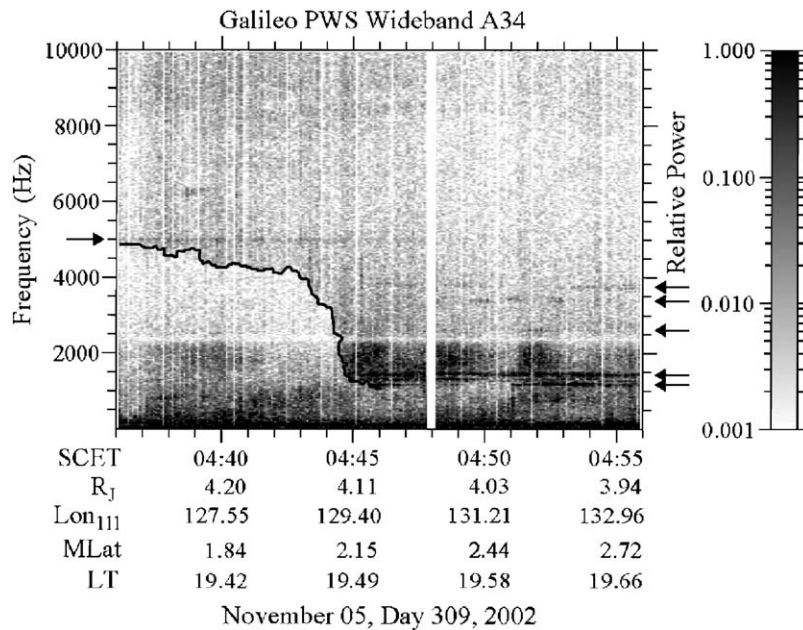


Fig. 6. Plot of the high-resolution data from the wideband instrument on board Galileo. This instrument was in a mode to monitor frequencies less than 10 kHz at the time. The dark line is f_{cutoff} . Note the banded emission lines for $f < 5$ kHz, indicated by arrows.

Green and Gurnett (1980) have shown that L–O-mode emission for frequencies as low as 56 kHz from sources close to Jupiter along the Io flux tube propagate away from the Io torus, leaving an emission shadow zone. We point out that the low energy electron density in the JIR is believed to be quite low, much lower than the “inner plasmasphere” values of Divine and Garrett (1983), and clearly much lower than the Io torus. We cite the work of Warwick and Dulk (1964) and Dulk et al. (1992) who found that the nearly 100% elliptical polarization of Jupiter’s decametric emission implies a high-latitude density with an upper limit of about 5 cm^{-3} .

Another interesting feature of Fig. 6 is the emission bands that exist for $f_{\text{cutoff}} < f \lesssim 5 \text{ kHz}$. These emission bands persist until the end of the data near 06:30. These emission bands are believed to be natural emission, not spacecraft interference, because the bands have a definite start time (they are not present for earlier times) that is strongly associated with the plasma boundary at f_{cutoff} . In addition, no similar interference bands at these frequencies have been observed in the past. A particularly intense emission band is observed near 5 kHz in Fig. 6. This same band is seen even more intensely at later times in Figs. 1 and 3. We have performed direction finding for this band at 4.98 kHz and note that the emission appears to come from a high-latitude source in a direction very similar to the emission from 563 Hz, and consequently close to the directions obtained for all the other high-latitude source frequencies. These results are not included in Fig. 1. The appearance of the emission is similar to narrowbanded radio emission associated upper hybrid bands, $f_{\text{UH}} = (n + 1/2)f_c$ observed at Earth near the plasmopause magnetic equator (cf. Kurth, 1992, Fig. 2). The bands are also similar to radio emission identified as Jovian continuum emission (Fig. 3 of Kurth, 1992). Such emission is believed to be at least partially O-mode emission. There are both linear and nonlinear theories for the generation of continuum emission (cf. Jones, 1988, and Ronnmark, 1992, respectively), but both theories are based on the conversion of electrostatic upper hybrid bands to electromagnetic waves. In the linear mechanism UH waves refract (in a steep density gradient) to Z-mode waves at a wave normal angle near 90° . Z-mode waves can mode convert to O-mode waves (cf. Horne, 1989, 1990). The nonlinear mechanisms are described by the authors as more efficient than the linear conversion mechanism. For these processes UH waves coalesce with some lower frequency wave.

6. Conclusions

The direction finding of the Galileo A34 plasma wave data combined with knowledge of the magnetic field

orientation and higher resolution wideband data have been combined to produce a more complete picture of the radio emissions. The Galileo spacecraft penetrated the cold plasma torus on its way to the Jovian inner magnetosphere. Analysis of spin modulation of radio emission for $r < 4 R_J$ (within the JIR) indicates two distinct source regions of emission, one at low latitude and another at high latitude. While the data are not conclusive, the radio emission is consistent with L–O-mode emission perhaps mixed with Z-mode at the higher frequencies and whistler mode for $f \lesssim 1 \text{ kHz}$. Emission near 250 kHz is probably O-mode as determined from a lack of sensitivity to the local cyclotron frequency.

The O- and Z-mode emission observed from sources at low latitude from the inner edge of the cold torus (JIR) probably results from mode conversion as hypothesized for terrestrial continuum and kilometric continuum emission near the Earth’s plasmopause. This is the same mechanism that generates nKOM emission from sources in the outer torus. The nKOM emission would not be visible from the JIR due to the dense plasma of the Io torus between the sources of nKOM and the JIR unless there were density gaps and inhomogeneities in the torus. The observed attenuation lanes are possibly due to emission from distant and distinct radio sources near the outer edge of the central low-latitude density peak of the cold Io torus that is blocked from view by attenuating foreground plasma near the magnetic equator. This attenuation is required by the results of the direction finding to be near the magnetic equator for emission at $f > 80 \text{ kHz}$.

A possible source of the radio emission observed from high-latitude source regions is the O-mode radio emission source identified by Kaiser et al. (1993) along a high-latitude ($L = 16$) magnetic field line. This emission might be consistent with our results also, especially for the emission at frequencies $5 \text{ kHz} < f < 10 \text{ kHz}$ observed in the Galileo wideband data which does not appear to have the narrowbanded emission structures associated with it. No such banded morphology was seen in the radio emission observed by Ulysses and reported by Kaiser et al. (1993) (cf. their Fig. 3). The emission observed by Kaiser et al. for $5 \text{ kHz} < f < 50 \text{ kHz}$ did not have the attenuation lane seen in the data presented in this paper (for $15 \text{ kHz} < f < 35 \text{ kHz}$), but that may be explained by the different observing positions of Galileo and Ulysses. Galileo was within the JIR and near the Jovigraphic equator. Ulysses observations of the O- and Z-mode emissions were obtained while the spacecraft was at a radial distance of about $17 R_J$ and only at the maximum latitude during each planetary rotation. The minimum spacecraft latitude was greater than 17° when Ulysses observed the emission. The Io torus strongly refracts radio emission from the Jovian auroral region, thus it is possible that if an attenuation lane was present in the

O- and Z-mode emissions near the source region, it was subsequently obscured by propagation effects of the Io torus.

The measured location for the source indicated a centroid near about 200° CML extending to a radial distance of $3.8 R_J$. This is greater than 50° away from the Galileo observations, but it is possible that the source reported by Kaiser et al. (1993) extends in longitude, but was not observable due to the refractive effects of the Io torus. Refraction effects were not considered by Kaiser et al. (1993) in determining the direction and size of the source region. One must also consider temporal changes of the Jovian magnetosphere between the time of the Ulysses flyby and the Galileo observations.

The sKOM emission was observed by Ulysses in the southern hemisphere in the range $120^\circ < \lambda_{III} < 230^\circ$, which overlaps the range of Galileo observations discussed here. The observations of sKOM were made for $f \gtrsim 40$ kHz. The absence of sKOM for $f < 40$ kHz could be due to the weak nature of the emission as observed by Ulysses for $r > 47 R_J$ or obscuration due to the refractive effects of the Io torus. It is also possible that the emission observed by Galileo within the JIR from high-latitude source regions is neither that observed by Kaiser et al. (1993) or Reiner et al. (1994), but is a newly identified component.

The emission bands seen in Fig. 6 for $f < 5$ kHz appear to have a high-latitude source region. The bands look similar to upper hybrid resonance harmonic bands, $f_{UH} = (n + 1/2)f_{ce}$, that are seen near the terrestrial plasmopause (cf. Kurth, 1982). This suggests that the high-latitude inner radius of the plasma torus is analogous to the terrestrial plasmopause and the emission generation mechanism may be similar to terrestrial continuum, which is believed to be generated by a mode conversion of Z-mode to O-mode in the presence of strong density gradients. Green and Gurnett (1980) have reported that L–O mode emission from sources near Jupiter on field lines connecting to Io at $f = 56$ kHz refracts away from the magnetic equator on its propagation down the magnetotail. However, this should not be the case for emission at $f < 50$ kHz from the JIR, because this region of the Jovian magnetosphere has a much lower density than the Io torus.

While it is possible to place some constraints on the observations, definitive answers to some of the questions raised by the data must await a future mission.

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