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Narrow-band kilometric radio emission as observed by the Galileo plasma wave instrument

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Abstract

Jovian narrow-band kilometric (nKOM) radio emissions have been well-studied, and are believed to have source regions near the outer edge of the Io torus. Recent investigations have indicated that these emissions increase in intensity associated with magnetic storm-like behavior in the Jovian magnetosphere. The orbit of Galileo affords the opportunity to pass close to the suggested source region near each perijove. We have examined the plasma wave spectra of nKOM on all orbital passes, and we present three cases in some detail. The nKOM emission is seen to increase in intensity at the outer edge of the plasma torus near the edge of the magnetic equator/current sheet crossings. Near perijove, and also associated with magnetic equator crossings, intense bursty (probably electrostatic) and narrow-banded emissions similar to upper hybrid emission seen at Earth are observed. We postulate that these emissions are related to the source of the nKOM emission. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Jovian narrow-band kilometric (nKOM) radio emission was first reported from the Voyager radio emission data (Warwick et al., 1979; Kaiser and Desch, 1980). The emission is characterized by its obvious narrow band (~ 50 kHz) and its relatively smooth morphology. Daigne and Leblanc (1986) reported the emission to be LHC 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, 1987a, b; 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 $9r_J$. The Ulysses observations of nKOM were best presented by Reiner et al. (1993) using the unique direction finding characteristics of the Unified Radio and Plasma Wave experiment (URAP). The results rather surprisingly indicated that the nKOM originates from a number of distinct sources located at different Jovian longitudes and latitudes and at the inner and outermost regions of the Io plasma torus. In fact, some of the source regions indicated by Reiner et al. (1993) were well away from the centrifugal equator. While both RH and LH polarization were observed, the results from sources in the outermost torus seem to favor the X-mode. This puts new constraints on the theoretical models.

Most recently, Louarn et al. (1998, 2000) have shown the recurrent intensifications of hectometric emissions (HOM) which have an auroral source, and nKOM emission. Louarn et al. (1998) have suggested these intensifications are related to plasmasheet thinnings and thus Jovian storm-like processes. Menietti et al. (1999) have further shown that Jovian HOM and decametric (DAM) emission at higher frequency, and also with a probable auroral source region, show time-averaged power enhancements on the nightside compared to the dayside, similar to terrestrial observations of auroral kilometric radiation (AKR). Since terrestrial AKR is known to be strongly correlated with electron precipitation into the nightside magnetosphere, these observations also imply Jovian magnetic storm-like processes. Reiner et al. (2000) have further reported a strong association of intense bKOM followed by nKOM that is triggered by IMF sector boundary crossings. All this recent work clearly shows the importance of a better understanding of the source regions and source mechanisms of the Jovian kilometric radio emissions. We report on recent observations of the source

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location of nKOM emission observed by the Galileo plasma wave instrument.

2. Instrumentation

The plasma wave receiver on board Galileo consists of four different swept-frequency receivers that cover the frequency range from 5.6 Hz to 5.6 MHz for electric fields and 5.6 Hz to 160 kHz for magnetic fields. For this study only electric field data obtained by the middle- and high-frequency receivers will be analyzed, covering the frequency range from about 42 Hz to 5.6 MHz. A single electric dipole antenna with a tip-to-tip length of 6.6 m is connected to each electric receiver. A complete set of electric field measurements is obtained every 18.67 s with a frequency resolution of about 10% (cf. Gurnett et al., 1992).

3. Observations

We have examined the radio wave data near perijove for each orbit of the Galileo mission to date. Of the 16 perijove passes examined, nine had intense nKOM emission present for $r < 20r_\mathrm{J}$, and seven had only very weak or no nKOM in this region. We present data from two of the first group of passes, which show that the nKOM is observed at high magnetic latitudes for $r \gtrsim 20r_\mathrm{J}$, but near perijove intense emission is observed associated with the magnetic equator. There was only one anomalous case (orbit C19) of intense emission near perijove but not near the magnetic equator. We also present data on an additional pass, C22, in which the orbit of Galileo lay within the Io torus for a long period. This latter pass is considered independently of the other 16 orbits.

In Fig. 1 we display a frequency–time spectrogram of the Galileo plasma wave observations for a three-day period from day 259–261 of 1997 (the C10 orbit). During this time the satellite approaches Jupiter from about $35r_\mathrm{J}$ at 00:00 UT on day 259 to about $9.17r_\mathrm{J}$ at 23:10 UT on day 261 (near the right edge of the plot). The frequency scale ranges from 100 Hz $< f <$ 5.6 MHz. Identified on the plot are decametric (DAM) and hectometric (HOM) emissions ($f >$ 300 kHz) (cf. Carr et al., 1983); narrowband kilometric emission (nKOM) in the approximate range 50 kHz $< f <$ 200 kHz; continuum emission ranging from approximately 1 kHz $< f <$ 15 kHz; and a narrowbanded emission near perijove labeled as upper hybrid. The gyrofrequency, f_ce, is indicated with a white line, and magnetic equator/current sheet (meq/cs) crossings are easily seen as minima in f_ce for $r > 12r_\mathrm{J}$. This time period was chosen because it shows a number of different types of emissions and is representative of the behavior of those passes with intense nKOM near perijove. Significant in this figure is the increasing intensity of nKOM as the satellite approaches perijove and the association of the intense nKOM with meq/cs crossings near perijove. For larger radial distances, generally the nKOM is observed at larger magnetic latitudes, but as the radial distance decreases ($r \lesssim 20r_\mathrm{J}$) the nKOM becomes quite intense and is observed within 5° of the meq/cs. We found this to be the case on eight of nine perijove passes with intense nKOM. The one anomalous example occurred on orbit C19.

Fig. 2 more clearly shows the nKOM associated with the magnetic sheet crossings near 09:15 and 19:30 on day 260 and near 06:00 on day 261. The nKOM appears as a narrowbanded emission confined in time and showing spin modulation characteristic of emission from a distant relatively small source region (cf. Menietti et al., 1998). In particular, for the crossing near 09:15 the low-frequency cutoff of the most intense yellow nKOM ($E_\mathrm{peak} \approx 9.5$ μV/m) increases from about 08:15 to about 09:30, corresponding closely to the current sheet crossing (see arrows in Fig. 2). Fig. 2 also clearly shows the low-frequency cutoff of the continuum emission indicated near 04:15 and 09:15 of day 260. The low-frequency cutoff of this emission is believed to indicate the local plasma frequency (cf. Kurth, 1992). These continuum emission cutoffs clearly indicate a density peak centered near the meq/cs. The continuum emission disappears after about 18:00 on day 260, probably due to the spacecraft entering the radio shadow of the Io torus.

The nKOM observed near 19:30 ($E_\mathrm{peak} \approx 17$ μV/m) in Fig. 2 is even more intense than the episode near 08:30, and the low-frequency cutoff of the most intense emission (yellow color) shows an interesting oscillation that is not centered with respect to the current sheet crossing. The increase in spectral density is about twice that expected due only to a change in distance from a fixed source ($1/r^2$ effect). There is no continuum emission at this small radial distance to confirm the local density gradient. Quite near the meq/cs at about 19:30 intense electrostatic electron cyclotron emission (EEC) is observed just above f_ce. These emissions are indicative of a gyrotropic electron distribution with many trapped particles as expected near the magnetic equator. Finally, we note that the nKOM emission near 06:00 on day 261 is even more intense ($E_\mathrm{peak} \approx 30$ μV/m) and is almost centered with respect to the meq/cs.

In Fig. 3 we display a high time resolution plot which includes perijove. Here we observe intense nKOM near the meq/cs close to 16:30 of day 261, and a narrowbanded emission with a central frequency that reaches a peak near perijove. The nKOM emission is in the same frequency range as that observed in Fig. 2. The low-frequency cutoff of the nKOM reaches a maximum very near the meq/cs (perhaps the centrifugal equator) at about 16:30 near the intense EEC emission. This nKOM emission is different in morphology than that seen earlier in Fig. 2. It is extremely intense ($E_\mathrm{peak} \approx 0.13$ mV/m), has a smaller frequency extent, and is quite bursty compared to the nKOM emission seen in Fig. 2. There is also no spin modulation of this emission. We believe that this emission is consistent with a

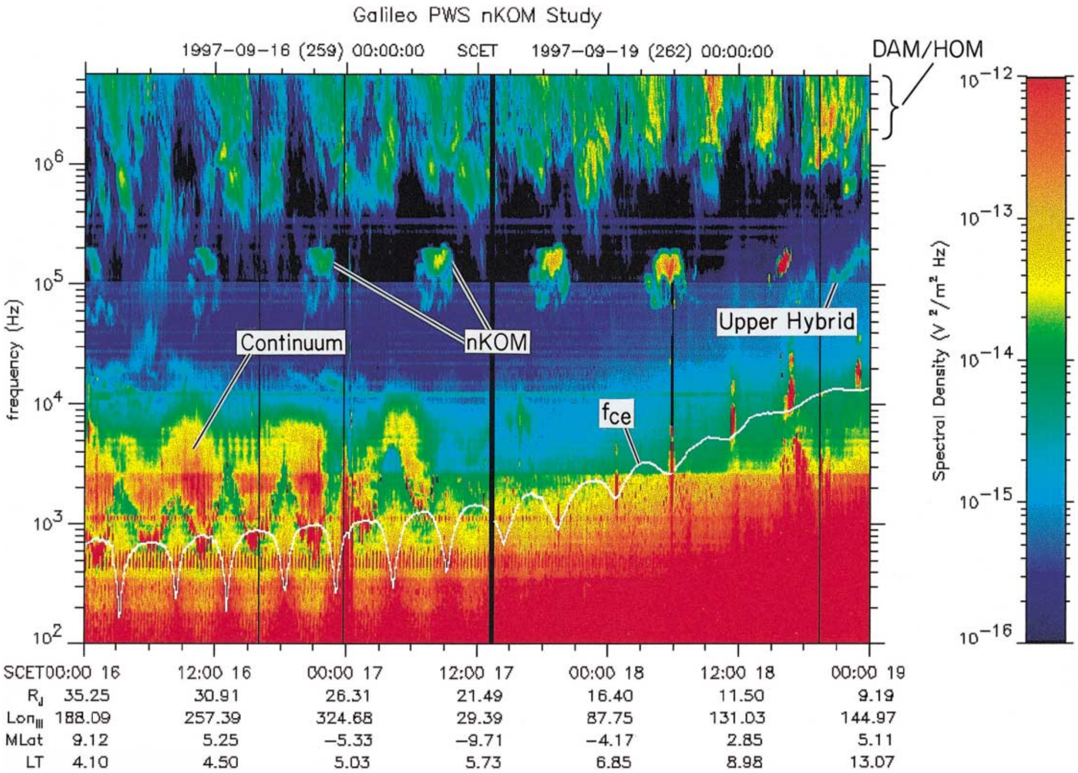

Fig. 1. A frequency–time spectrogram of the Galileo plasma wave observations for a 3-day period from days 259 to 262 of 1997 (the C10 orbit). Several distinct types of radio emission are indicated as defined in the text: DAM, HOM, nKOM, continuum, and upper hybrid. The gyrofrequency, $f_{\rm ce}$, is indicated with a white line, and magnetic equator/current sheet crossings are easily seen as minima in $f_{\rm ce}$ for $r > 12r_{\rm J}$.

mixture of electrostatic and electromagnetic emission, but we cannot confirm this because the magnetic receiver does not measure frequencies this high. This region could be very near the source region of the nKOM. Intense, isolated bursts (probably electrostatic) are seen at the same time as the EEC emission ($\sim 16:45$). The narrowbanded emission which begins at about 18:00 is not as intense and shows a low-frequency cutoff that shows three distinct peaks near 18:30, 20:30, and finally within 1.5° of the meq/cs at 23:15. This fainter emission has the morphology of upper hybrid emission (UH) often observed by Galileo near satellite closest approach (cf. Gurnett et al., 1996), and often near magnetic equator crossings in the Earth's magnetosphere (Gurnett, 1975; Kurth, 1982; Morgan and Gurnett, 1991). If we interpret this emission as upper hybrid emission then the median frequency is close to the cold plasma expression $f_{\rm UH} = \sqrt{(f_{\rm pe}^2 + f_{\rm ce}^2)}$. The three peaks in frequency of this emission indicate density enhancements that are not all associated with the current-sheet crossing. Perhaps these indicate asymmetries in the density profile of the plasma torus either with respect to radial position, magnetic latitude, or longitude. Such asymmetries have been observed in the past (Desch et al., 1994).

Fig. 4 shows a second example of the nKOM emissions for the time interval 21:00 of day 150 to 09:30 of day 152 of 1998 (orbit E15). The similarity between this example and that of Fig. 1 is obvious. The nKOM emissions seen near 23:30 of day 150 ($E_{\rm peak} \approx 22$ μV/m) and 10:00 of day 151 ($E_{\rm peak} \approx 17$ μV/m) are very intense and are centered relative to the meq/cs (similar to the emission near 06:00 in Fig. 2). The emission labeled nKOM centered near the meq/cs at about 20:50 on day 151 is similar in morphology to that labeled nKOM in Fig. 3. This emission is relatively bursty with a smaller bandwidth than other emission labeled nKOM in the figure. Some of the bursts have $E_{\rm peak} \approx 48$ μV/m. As in the case of Fig. 3 near 16:30, we believe this emission is a mixture of electrostatic and EM emission and could be near the source region of nKOM. In Fig. 5 we display the upper hybrid-like emissions at higher time resolution. This emission has a maximum frequency about 15 min before the time of the most intense wave power ($E_{\rm peak} \approx 16$ μV/m), which occurs associated with the intense EEC emission near the meq/cs crossing.

The emission in Fig. 5 shows spin aliasing which allows direction finding of the source region as described in Menietti et al. (1998). The spectral density of this emission is most intense when the wave electric field makes an angle of approximately 70 ± 15° with respect to the ambient magnetic field. This large angle is consistent with emission that is mainly electrostatic upper hybrid emission, which has an

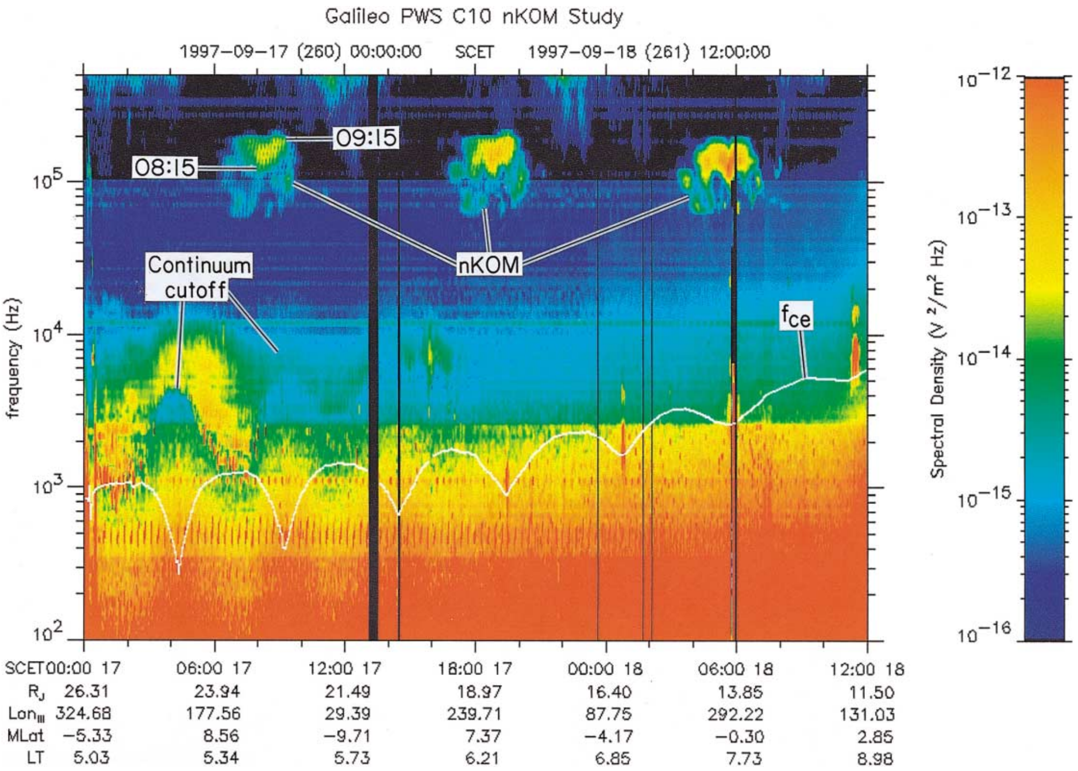

Fig. 2. A higher resolution portion of Fig. 1 which more clearly shows the nKOM associated with the magnetic sheet crossings near 09:15 and 19:30 on day 260 and near 06:00 on day 261. In particular, for the crossing near 09:15 the low-frequency cutoff of the intense nKOM increases from about 08:15 to about 09:15 (note the arrows), corresponding to a density gradient indicated by the low-frequency cutoff of the continuum emission. The nKOM emission near 06:00 is almost centered relative to the meq/cs.

electric field that is nearly perpendicular to the magnetic field (cf. Stix, 1992).

The spacecraft observed nKOM emission on alternate crossings of the meq/cs. This can be explained by a nKOM source region that is localized in longitude as the Ulysses observations of Reiner et al. (1993) have indicated. The linear generation mechanism for nKOM suggested by Jones (1985, 1986, 1987a, b) or Horne (1989, 1990) and the nonlinear mechanism proposed by Ronnmark (1983, 1989, 1992) require the presence of intense upper hybrid emission associated closely with the nKOM (cf. Kurth, 1992). Typically the observations show upper hybrid-like emissions (as in Figs. 2 and 5), sometimes intense, but not directly connected to intense nKOM. This could also be explained by the spacecraft not being at the correct system III longitude as the source.

The last example presented is from a portion of orbit C22 which we consider independently of the other nine orbits with intense nKOM near perijove. At this time Galileo was undergoing a dramatic change in its orbit shape in preparation for orbit I24, a flyby of Io. The orbit, originally highly elliptical with an apogee of over $100r_J$, at the time of orbit C22 is much more circular, lying inside the Io torus for much of the time. In Fig. 6 we show a frequency–time spectrogram for a 20-h period overlapping days 223 and 224 of 1999. We observe that the satellite is within the Io torus ($r < 10r_J$) during most of this period. Now possible nKOM emission is seen associated with upper hybrid emission that persists in time (longitude) and is not just observed near perijove as in the other orbits we have presented. Due to the spacecraft motion the two events referred to as possible nKOM in Fig. 6 occur over 12 h apart in UT, but at nearly the same system III longitude. In addition, the EEC waves observed between about 12:00 and 15:40 UT on day 224 are seen as multiple bands of harmonics and appear directly associated with emission that may be nKOM. Unfortunately, the magnetic field data for this time period does not confirm that this emission is electromagnetic. The sensitivity of the search coils in the frequency range of this emission has degraded too severely since launch to be able to confirm this assumption. A higher resolution of this emission is seen in Fig. 7. The emission seen in the time interval from about 03:00 to 06:00 is typical in morphology to upper hybrid emission observed at Earth for instance, and is seen associated with EEC emission and its harmonics. In Fig. 6 intense EEC emission and its harmonics seen near 22:30 UT persists in a band at lower intensity levels at the fundamental frequency until it becomes very intense again near 04:30 UT (day 224). Between 22:00 (day 223) and 02:00 (day 224) intense emission very similar in morphology to nKOM (with similar bandwith and central frequency, but more bursty) is observed. This more bursty morphology may be due to a mixture of both electrostatic and electromagnetic emission

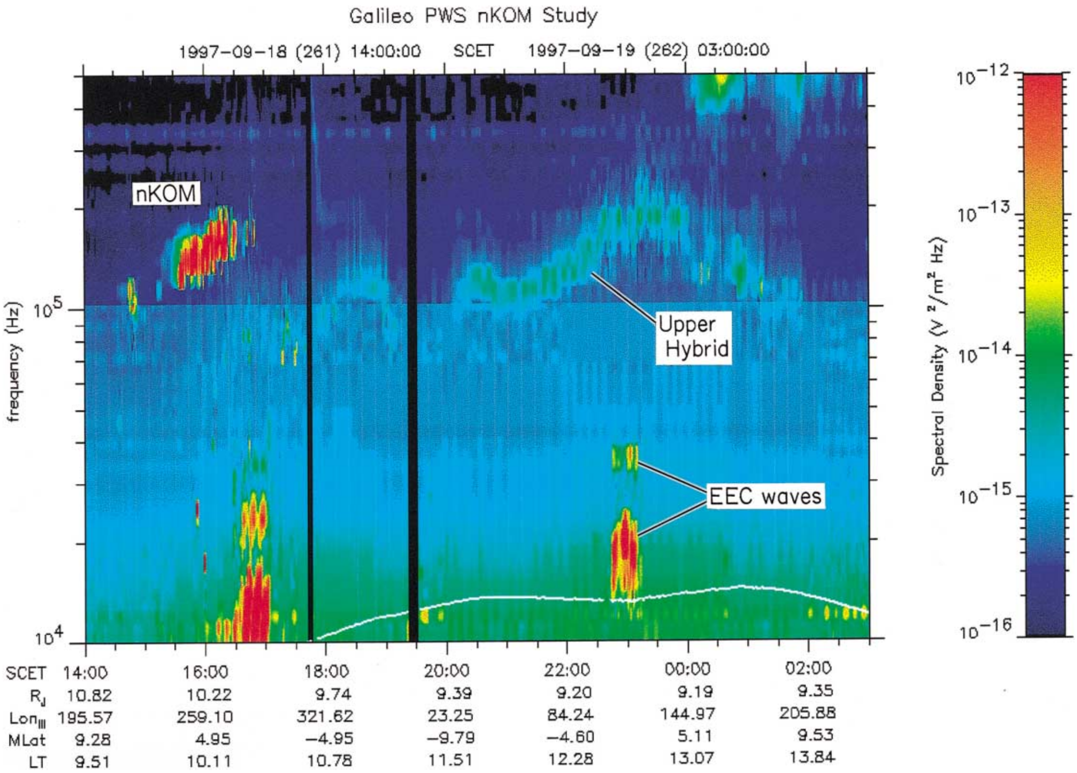

Fig. 3. A high time resolution plot which includes perijove. Here we observe intense, bursty nKOM near the meq/cs close to 16:30 of day 261, and a narrowbanded emission, which we interpret as upper hybrid, with a central frequency that reaches a peak near perijove. The low-frequency cutoff of the nKOM reaches a maximum very near the meq/cs at about 16:30 in close association with the intense electrostatic electron cyclotron (EEC) emission seen near the same time.

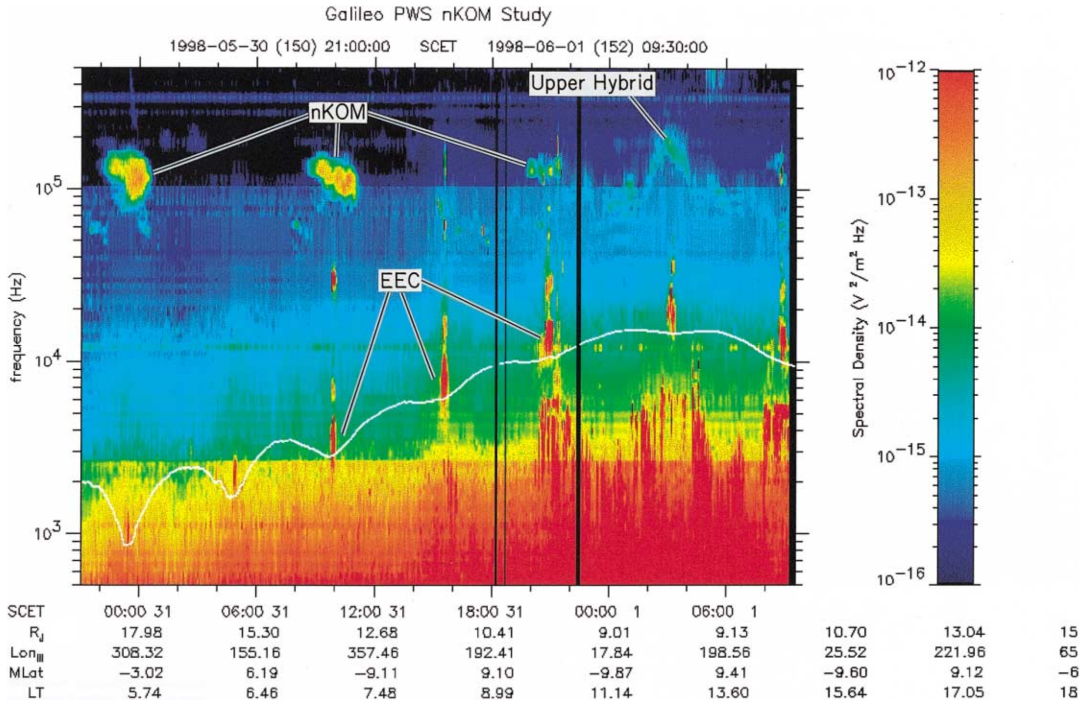

Fig. 4. A second example of the nKOM emissions for the time interval 21:00 of day 150 to 09:30 of day 152 (1998). The similarity between this example and that of Fig. 1 is obvious.

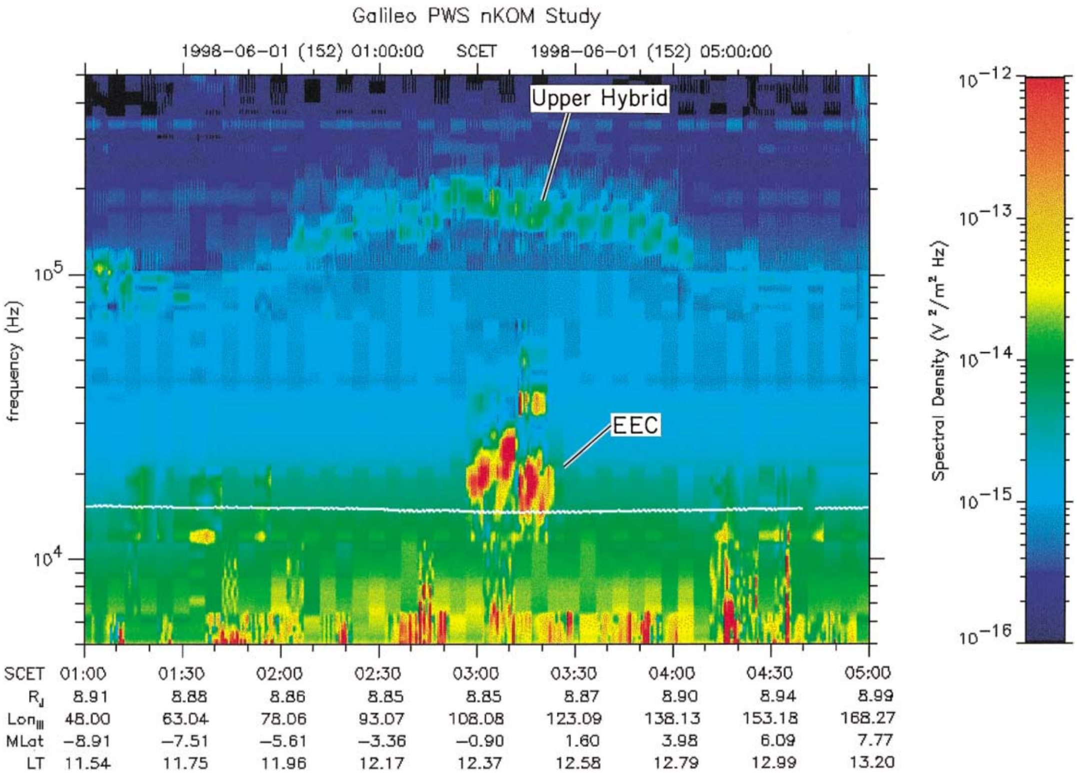

Fig. 5. A higher time resolution of the upper hybrid-like emissions seen in Fig. 4. This emission has a maximum frequency about 50 min before the time of the most intense wave power, which occurs associated with the EEC emissions near the center of the meq/cs crossing.

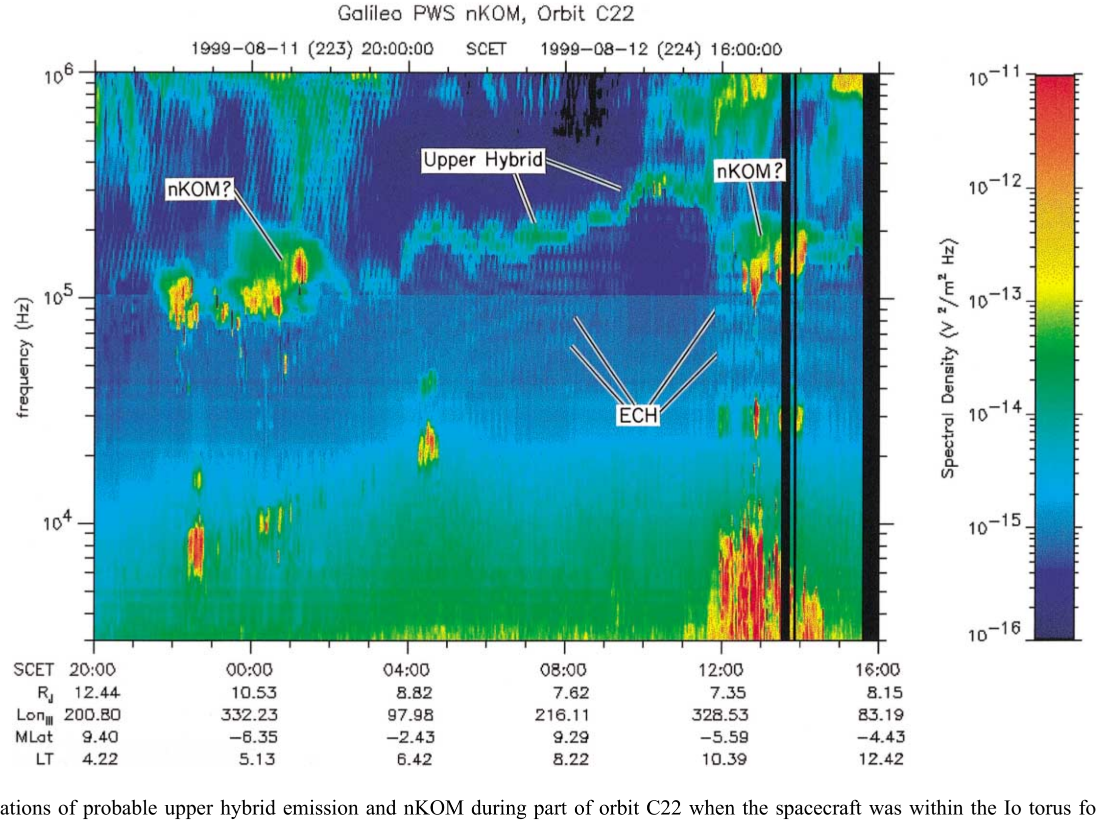

Fig. 6. Observations of probable upper hybrid emission and nKOM during part of orbit C22 when the spacecraft was within the Io torus for an extended period of time. Note EEC harmonics persisting in longitude and possible nKOM associated with the upper hybrid emission.

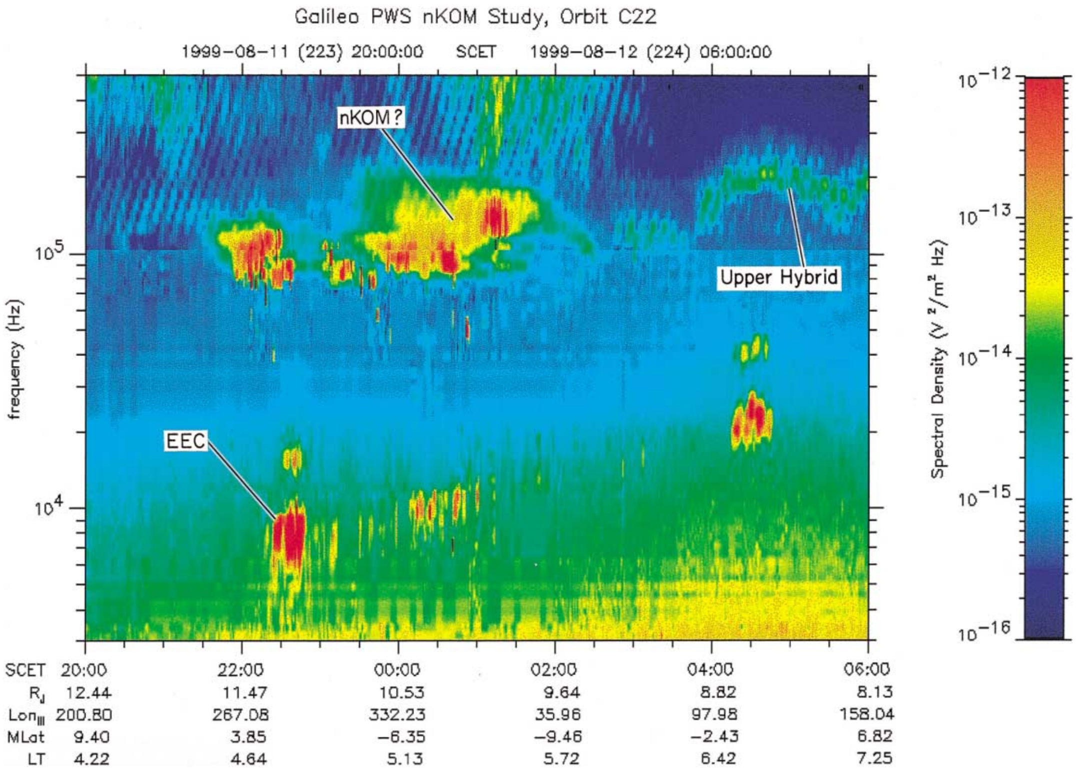

Fig. 7. A higher time resolution of some of the emission of Fig. 6 showing an EEC fundamental emission band, upper hybrid emission, and possible nKOM emission.

and indicate that the satellite is near the source region of nKOM. More possible nKOM is observed between about 12:30 and 14:15 on day 224 in the approximate frequency range 100 kHz $< f <$ 200 kHz (Fig. 6).

Some of the data shown in Fig. 7 shows a spin aliasing and we have performed an analysis of this information as before for the case of day 152 of 1998. We find that for the time period of about 00:00 to 01:00 on day 224 at a frequency of 176 kHz, the emission is most intense when the antenna is within 10° of the ambient magnetic field. This would be consistent with transversely propagating electromagnetic radiation such as nKOM (cf. Menietti et al., 1998). However, for the time interval from about 04:00 to 05:00 at a frequency of 201.6 kHz, the emission shows peak intensity when the antenna is within 10° of being perpendicular to the magnetic field, consistent with upper hybrid emission. The statistical error in this analysis is about 10°.

4. Summary and conclusions

The Galileo mission has shown increasing evidence for a dynamic, storm-like magnetosphere in many ways similar to Earth's. Radio emissions over a broad range of frequencies are observed to display storm-like events that are independent of Io phase and most likely controlled by internal processes associated with plasma sheet thinning. Most recently, both HOM and nKOM emissions have been shown to be indicators of these Jovian "energetic events" (cf. Louarn et al., 1998, 2000; Reiner et al., 2000). In this work, we have investigated the morphology of nKOM emission during perijove passes of the Galileo satellite. The orbit of Galileo allows a detailed investigation of nKOM that has not been possible in the past from the flyby missions of Voyager and Ulysses. We have conducted a survey of nKOM emission observed near perijove for each orbit of the Galileo mission to date. Of the 16 perijove passes examined, nine had intense nKOM emission present for $r < 20r_J$, while seven had no or weak nKOM. On eight of the nine perijove passes with intense nKOM, this emission is observed at high magnetic latitudes for $r \gtrsim 20r_J$, but near perijove intense emission is observed near the center and edges of the meq/cs (Figs. 1–4). The one anomalous example occurred on orbit C19. Emission that resembles upper hybrid emission was observed near perijove on 13 of the 16 passes and on all of the passes with intense nKOM near perijove. There was only one case of intense upper hybrid emission without intense nKOM near perijove. The low-frequency cutoff of the most intense nKOM appears to be associated with the density gradient (relative to magnetic latitude) within the torus, but a similar frequency-dependent cutoff might also be explained by refraction near the magnetic equator or by a radio beam occultation by a high-density region. Near perijove ($8r_J \lesssim r \lesssim 9r_J$) emission most likely identified as upper hybrid is observed, perhaps mixed with electromagnetic emission. Intense nKOM emission appears to be localized not only in radius but also in longitude, because it is usually observed on alternate passes of the meq/cs, and the intensity of the upper hybrid emission observed near perijove varies much in intensity orbit by orbit. Near perijove the highest frequency UH emission is sometimes not coincident with the magnetic equator crossing. This probably indicates the effects of centrifugal forces on the plasma. Much of Orbit C22 lies within the Io torus (Figs. 6 and 7) and provides some of the best observations of upper hybrid emission seen at the same radial distance and longitude as nKOM emission.

These observations are consistent with the theories of the linear source mechanism of nKOM proposed by Jones (1985) or the nonlinear mechanism proposed by Ronnmark (1992) for the production of O-mode emission by mode conversion of upper hybrid emission. Gurnett et al. (1998) point out that Europa appears to be a site of enhanced upper hybrid emissions near 100 kHz. Such emissions may also play a role in the generation of some nKOM. Kurth (1982) did observe a direct association of upper hybrid emission with narrowband electromagnetic radiation near the terrestrial plasmapause, but such observations are indeed rare even for the terrestrial magnetosphere. We suggest that the nKOM emission has a source mechanism that is similar to that of terrestrial narrowband electromagnetic radiation. The bursty "nKOM" emission observed near 16:00 in Fig. 3, near 21:00 in Fig. 4, and that of Fig. 7 may be the result of a mixture of electrostatic and electromagnetic emission near the source region of nKOM. The most intense bursts of emission in these regions and the most intense bursts of emission believed to be upper hybrid or other electrostatic emission have electric field strengths over an order of magnitude larger than nKOM emission observed with smoother morphology and showing spin modulation typical of a more remote source (such as seen in Fig. 2). This increase in wave power is much more than expected for a $1/r^2$ increase and is consistent with the required field strengths of electrostatic waves necessary to generate O-mode emission by linear wave mode conversion as suggested by Horne (1990) or Jones (1985). We also point out, however, that due to the finite response time of the plasma wave receiver, the measured field strengths of bursty emission could be much higher. The measured values represent averages over the integration time for each frequency channel. The plasma wave instrument on board Galileo (PWS) cannot determine the polarization of the emission. We note that Reiner et al. (1993) observed nKOM emission with both left- and right-hand polarizations, but reported that the nKOM emission with sources located in the outer torus seemed to favor extraordinary mode emission. This would not be consistent with the above cited theories which all predict left-hand polarized ordinary mode emission.

Our observations indicate that for distances $r \gtrsim 20r_J$, the nKOM is observed at larger magnetic latitudes while near perijove nKOM often appears close to the magnetic equator (cf. Fig. 1). This could be a propagation effect due to refraction or occultation by the Io torus. The direction finding calculations of Reiner et al. (1993) have indicated nKOM sources that are near both the inner and outer edges of the torus, and some are well away from the magnetic equator. It is possible that those sources Reiner et al. (1993) indicated away from the magnetic equator may have only appeared so due to propagation effects. It might also be possible that sources well away from the magnetic equator exist simultaneously or at other times, such as in the case of the anomalous orbit C19 of our study.

In the future we will continue to monitor Jovian nKOM near perijove. Galileo is scheduled to make a number of additional orbits of Jupiter if it survives the intense radiation doses of the inner magnetosphere. Unfortunately, during the Cassini flyby of Jupiter in mid 2004, Galileo is now planned to be outside the magnetosphere of Jupiter.

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