

LANE FEATURES IN JOVIAN HECTOMETRIC RADIO EMISSIONS

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Abstract

Observations of Jovian hectometric radio emission (HOM) by the Planetary Radio Astronomy experiment (PRA) aboard the Voyager spacecraft show persistent spectral features which had not been previously studied. It is well known that the observed HOM is modulated by the rotation of the planet such that very little HOM activity is observed when the central meridian longitude is within $\pm 80^\circ$ of the longitude of the northern magnetic pole, but its occurrence probability approaches 100% at other longitudes. The features of interest appear as ‘lanes’ of decreased emission intensity within the otherwise persistent HOM, as displayed in spectrograms of frequency versus System III (1965) longitude. The lanes have well-defined, sloping, linear borders and have relatively consistent central meridian location in the spectrograms.

To study the phenomenon more closely and enhance the persistent features, data taken from a period of more than 40 planetary rotations before the Jovian encounter of Voyager 2 were combined and sorted into half-degree longitude bins. The emission occurrence probability was then calculated for each bin. Emission was determined to have occurred if the intensity at a given longitude and frequency exceeded a calculated background threshold. This technique brings out the stability of the lane features. Occurrence probability spectrograms of frequency versus magnetic latitude were also created from the portion of the data when the spacecraft was between 0° and $+10^\circ$ magnetic latitude in two different longitude ranges. The two spectrograms are quite similar despite the differences in longitude, indicating a symmetric aspect to the lane and emission features.

Ray tracing calculations have been made assuming: Hollow conical emissions about magnetic field lines consistent with the theory of generation of HOM through the cyclotron maser instability, the Divine and Garrett [1983] model plasma distribution, and the O₄ magnetic field model of Acuña and Ness [1976]. These calculations suggest that the lane phenomenon may be intrinsic to the source of the HOM emissions since it occurs at frequencies greater than that can be refracted by the Io torus, the most viable source for any propagation effects.

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1 Introduction

Ground-based radio wave data going back to the 1950's had indicated that Jupiter has an extensive magnetic field and complex radio wave emissions in the decametric and decimetric wavelength ranges. It has only been through spacecraft measurements that scientists have discovered additional complex Jovian radio emissions in the kilometric and hectometric wavelength ranges. The Planetary Radio Astronomy (PRA) instruments aboard the Voyager 1 and 2 satellites have provided detailed measurements of Jovian hectometric radiation or HOM.

The basic spectral characteristics of HOM, as measured by the PRA, show the frequency extent of the emission to be from approximately 300 kHz to at least 2 MHz. A generally recognized characteristic of HOM, when compared in frequency-time spectrograms to the other Jovian free-escaping radio emissions, is a lack of distinctively consistent morphological features such as the arc-like structures evident in the Jovian decametric emission. Figure 1 shows a typical frequency versus central meridian longitude (CML) spectrogram observed by Voyager 2 in the frequency band from 20 kHz to 1.2 MHz for one Jovian rotation. Dark represents the most intense and light the least intense emission (in millibels). The HOM emissions are seen from 40° to 120° and from 300° to 360°. Consistent morphological features are not easily discerned in examination of spectrograms rotation by rotation because of temporal variation of the emission.

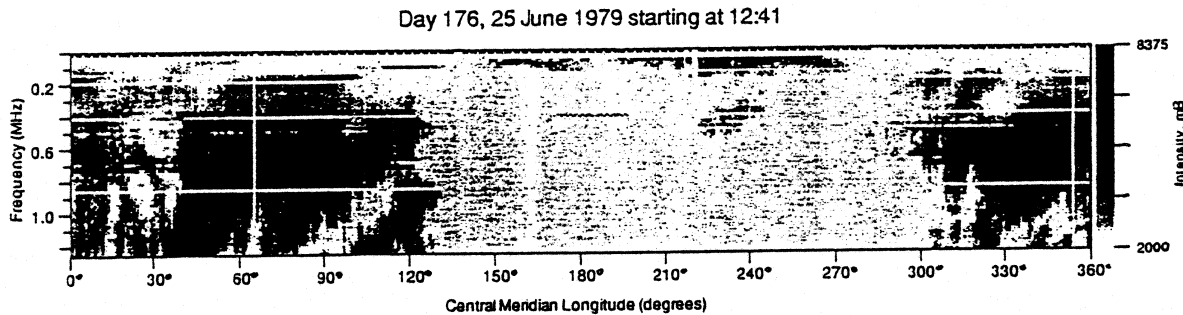


Figure 1: A frequency versus central meridian longitude (CML) intensity spectrogram from the PRA experiment onboard Voyager 2 taken during one planetary rotation prior to encounter with Jupiter. The HOM emissions are seen as a diffuse broad-band emission extending over a limited CML range.

The polarization of HOM have recently been investigated by Ortega-Molina and Lecacheux [1991]. Their findings strongly indicate that this emission is predominantly right-hand polarized when observed from the Jovian northern hemisphere and left-hand polarized when observed from the southern hemisphere. The polarization measurements have led these authors and many others to the conclusion that HOM is generated by the cyclotron maser instability (CMI) in the right-hand extraordinary (R-X) mode from high latitude source regions in both the northern and southern hemispheres.

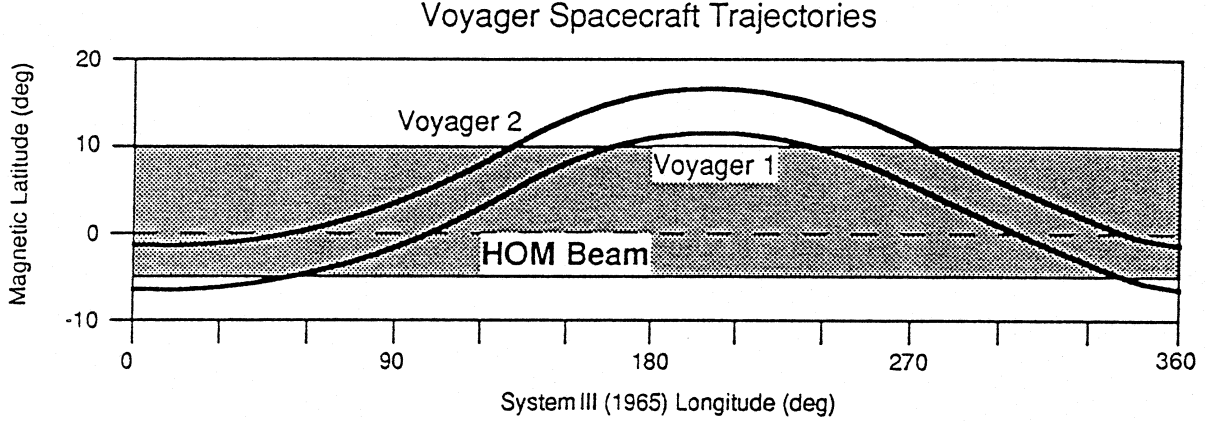


Figure 2: A summary of the observed emission beaming and polarization dependence of HOM is shown in this figure (adapted from Ladreiter and Leblanc [1990a]) of the Voyager 1 and 2 trajectories (at large radial distances) in magnetic latitude versus CML. The lack of HOM emissions from 120° to 300° CML (see Figure 1) is found when the Voyager 1 and 2 spacecraft are above $+10^\circ$.

The propagation characteristics of HOM have recently been studied by Ladreiter and Leblanc [1990a; and 1990b] by comparing observations with computer ray tracing calculations. These authors suggest that HOM is beamed from high altitude northern and southern hemisphere sources into the magnetic equator in overlapping right-hand and left-hand polarized hollow emission cones, respectively, bounded approximately by $\pm 10^\circ$ magnetic latitude. Figure 2 is a summary of the observed emission beaming of HOM. It illustrates that the lack of HOM emissions from 120° to 280° CML coincides with the time when the Voyager 1 and 2 spacecraft are above $+10^\circ$ magnetic latitude.

The purpose of this paper is to investigate peculiar emission characteristics found in the dynamic spectrum of HOM. Although the HOM emission appears to be featureless on casual examination, careful analysis of the frequency–time spectrograms reveals subtle but consistent linear features of decreased intensity within the otherwise amorphous HOM emission regions. We will show that by superimposing PRA data from multiple observations sorted according to longitude as well as magnetic latitude, and by using an occurrence probability technique (to take into account the variability in emission intensity), the low intensity HOM spectral features are enhanced. Lane features or absences of the radiation are clearly visible in the composite spectrograms in frequency versus CML and in frequency versus magnetic latitude. An explanation of these lane features should provide us with a better understanding of HOM emission characteristics, source region, and propagation effects in the inner Jovian magnetosphere.

Occurrence Probability Spectrograms 16 June – 6 July 1979

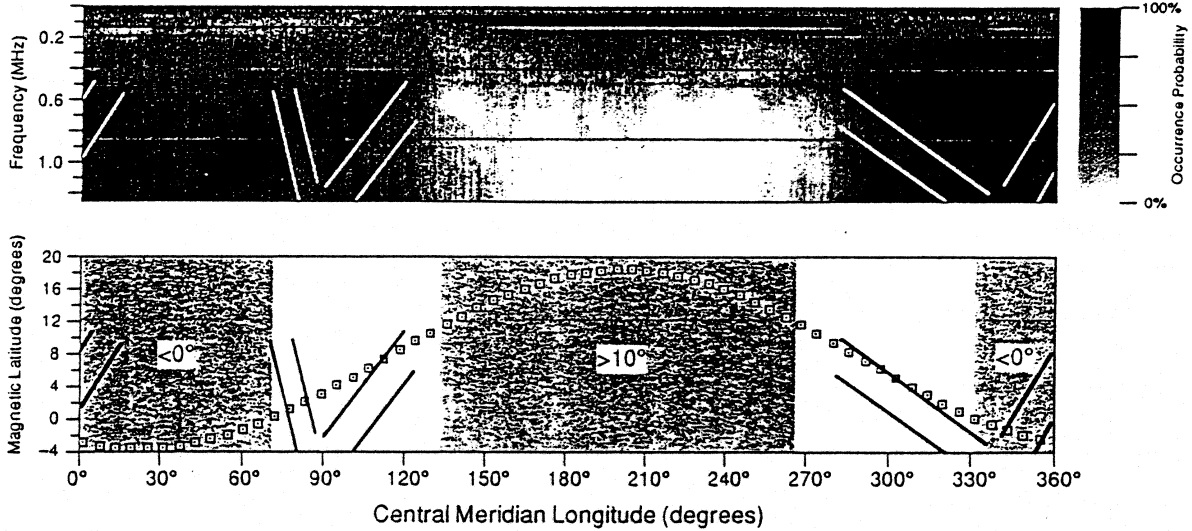


Figure 3: The top panel shows the occurrence probability spectrogram sorted by the wave frequency and CML. This technique provides an equal weight to stronger and weaker HOM events, reducing any intensity dependence of the emission. The top panel combines data taken from over 40 planetary rotations before Voyager 2 encounter and clearly shows that zones of decreases in the occurrence probability appear as ‘lanes’. The borders of the lanes are marked in white in the spectrogram. The bottom panel shows the magnetic latitude of the Voyager 2 spacecraft during the observations presented in the top panel. It can easily be seen that the lowest occurrence probability for HOM occurs when the spacecraft is above $+10^\circ$ magnetic latitude.

2 Data analysis

2.1 Occurrence probability: frequency versus CML

It has been demonstrated by Barrow and Desch [1989] as well as by others that the HOM emission intensity varies with solar wind density and/or solar wind pressure. From the examination of individual events of HOM, it is difficult to distinguish between seemingly random emissions and possibly repeatable characteristics due in part to the dependence of the emission on the solar wind. In order to enhance stable HOM features, multiple PRA observations with similar viewing geometries have been combined and analyzed by using a standard, intensity-independent occurrence probability normalization technique.

The top panel of Figure 3 shows the occurrence probability of HOM sorted by frequency and CML. In this figure, pre-encounter Voyager 2 PRA data from June 16 to July 6, 1979 are sorted in half-degree CML bins. This time period was selected due to the strength and consistent appearance of HOM in close proximity to Jupiter and yet at radial distances greater than 46 Jovian radii (R_J), so that only far-field effects of the

radiation with roughly constant viewing geometry are examined. In each CML–frequency bin, the occurrence probability is determined by the number of ‘activity’ counts divided by the total number of observing counts for that bin. An ‘activity’ count occurs when the observed emission exceeds a set threshold level calculated in accordance with the level of activity for that rotation. This technique provides equal weight to stronger and weaker HOM events, greatly reducing any intensity dependence of the emission. The top panel of Figure 3 combines PRA data taken over 40 consecutive planetary rotations.

Figure 3 clearly shows that HOM is observed to a high probability at longitudes from 280° – 360° and 0° – 120° . A closer examination of this high probability CML zone reveals regions of decreased probability within certain frequency and CML ranges, appearing as ‘lanes’. The lanes have reasonably well defined linear borders (marked in white in the top panel and black in the bottom panel), and are consistent in their location in CML and HOM emission frequencies. These lane features can often be discerned in the frequency–time (or –CML) spectrograms for individual rotations once one knows where to look. This can be seen by comparing the lane features as illustrated in the top panel of Figure 3 with the HOM observations shown in Figure 1. Low intensity HOM regions tend to coincide with regions of low occurrence probability.

It is important to note that the lane features in the top panel of our Figure 3 can also be seen in Plate 1 of Alexander et al. [1981] in both the pre– and post–encounter data from Voyager 1 and Voyager 2. However, there was no discussion or interpretation of the lane feature in that paper. In the following section we will further investigate these lane features.

2.2 Occurrence probability: magnetic latitude versus frequency

The bottom panel of Figure 3 shows the magnetic latitude of the Voyager 2 spacecraft during the period of observations presented in the top panel. It can easily be seen that the lowest occurrence probability for HOM occurs when the spacecraft is above $+10^\circ$ magnetic latitude (and possibly below -10°). In addition, the lane features discussed in the previous section occur most prominently when the Voyager spacecraft is making an excursion from the magnetic equator to $+10^\circ$ magnetic latitude or vice versa. However, lanes observed from the southern magnetic hemisphere are less prominent.

To further investigate the magnetic latitude dependence of these lane features, we have plotted in Figure 4 the HOM occurrence probability as a function of the Voyager 2 magnetic latitude and observed frequency. Only those data for which the magnetic latitude of the spacecraft is between 0° and $+10^\circ$ are used in this analysis (southern hemisphere observations in the shaded areas in the bottom panel of Figure 3 were excluded). In order to see any longitudinal differences, the first two panels in Figure 4 show separately the data from CML 70° to 130° (left panel) and from CML 265° to 335° (right panel). The third panel is a superposition of the first two. Jovian kilometric radiation is also seen in these plots at frequencies below 300 kHz and at magnetic latitudes greater than 6° and extends to higher magnetic latitudes than shown.

For the HOM emissions the following characteristics are discernable in Figure 4:

- The lower frequency boundary of the occurrence probability indicates the typical lower frequency extent of the HOM emission to be about 300 kHz.
- A lane or decrease in the HOM occurrence probability is seen starting at $+10^\circ$ magnetic latitude at 500 kHz and extending down to the magnetic equator for HOM frequencies greater than 1 MHz.
- HOM emissions below the lane are observed to higher magnetic latitudes (see upper boundary of both panels of Figure 4 between 0.5 to 1 MHz).
- The lane features at the different longitudes (first two panels) are observed at about the same magnetic latitudes and frequencies. All three panels are qualitatively similar in morphology.
- A double peak in the occurrence probability at 600 kHz and 1.2 MHz is observed from 3° to 7° magnetic latitude. This double peak spacing is roughly harmonic.

In the next section, ray tracing calculations will be used in an effort to better understand the above-noted characteristics of the HOM emissions.

3 Ray tracing calculations

3.1 Previous ray tracing results

Ray tracing calculations provide a framework to test theories of planetary radio emissions and can provide insight into additional constraints on existing theories. Information can be inferred from ray tracing calculations about source region characteristics such as its location and about refraction and reflection effects that may cause shadow zones where radiation is not allowed (not because of the characteristics of the generation mechanism but because of the intervening plasma between the source region and the observer).

The first ray tracing calculations, which describe many of the gross features of HOM, were done in two dimensions by Ladreiter and Leblanc [1990a]. Using the CMI emission mechanism model, where the wave frequency is expected to be slightly higher than the local electron gyro-frequency at the source and the radiation is emitted into a hollow emission cone, Ladreiter and Leblanc found that the most likely source region for HOM is located at high latitudes along an $L=20$ magnetic field line. This proposed source region

Figure 4: (color plot, next page) The three panels plot the HOM occurrence probability as a function of magnetic latitude and emission frequency for two CML ranges and in combination. Only those data for which the magnetic latitude of the spacecraft is from 0° to $+10^\circ$ are included. The first panel shows data from CML 70° to 130° and the second panel for CML 265° to 335° . The third panel is a merger of the first two. All panels clearly show lanes or decreases in the occurrence probability starting at $+10^\circ$ magnetic latitude at 500 kHz and extending down to the magnetic equator for HOM frequencies greater than 1 MHz.

is also quite appealing since it is near, if not within, Jovian auroral field lines which are believed to have some solar wind control.

Three-dimensional ray tracing calculations by Ladreiter and Leblanc [1990b] extended their earlier analysis and found that the source region should be distributed in all longitudes producing a ring shape as would be seen from looking down onto the polar regions of the planet. Their results match the observed polarization and basic HOM emission beaming characteristics. The explanation for the observed intense band of HOM observed only at the equator is believed to be the result of the intersection and overlap of the emission cones emanating from the high latitude sources in the northern and southern hemispheres.

In this analysis, we have used three-dimensional ray tracing calculations to investigate potential causes for the lane features. Specifically, propagation effects (i.e., Io torus) and generation of harmonic HOM are investigated.

3.2 Models and mechanisms used

The ray tracing program used in this study is nearly identical to the one developed and used by Green [1984]. Three-dimensional ray paths were calculated for a cold plasma [Stix, 1962]. The magnetic field is given by the O₄ model [Acuña and Ness, 1976] and the plasma density model of Divine and Garrett [1983] is used. It is believed that these are the best available models of the inner Jovian magnetosphere.

The ray tracing calculations performed in this study used many of the results obtained by Ladreiter and Leblanc [1990a,b], such as the emission mechanism and source region location and distribution. In brief, the HOM ray tracing calculations begin with the radiation generated along the L=20 field line by the CMI mechanism with sources near the fundamental harmonic of the local electron gyrofrequency (wave frequency is 5% above the local electron gyrofrequency) and near the second harmonic (approximately twice the local electron gyrofrequency). For the sake of comparison, the radiation is assumed to be beamed into hollow emission cones with initial wave normal angles, for both the fundamental and second harmonic emissions, at 85°. This particular angle was chosen to be consistent with the CMI mechanism and the values used by Ladreiter and Leblanc [1990a,b].

3.3 Ray tracing calculations

Ray tracing calculations were performed at 5 HOM frequencies ranging from 400 kHz to 1.2 MHz. Figure 5 plots three-dimensional HOM ray paths projected into a meridian plane near the longitude of a typical HOM source region (290° CML in this example) for sources emitting near the fundamental of the gyrofrequency. For illustrative purposes, the emission cones shown are from sources emitting 1.2 MHz and 400 kHz HOM. In the background of this figure are contours of the R-X cutoff frequency (in kHz) for the Jovian inner magnetosphere, including the Io torus, in accordance with the Divine and Garrett [1983] model. The magnetic field lines at an L value of 6, 12, and 20 are also shown. Based on the ray tracing calculations at 5 HOM frequencies, the following can be deduced:

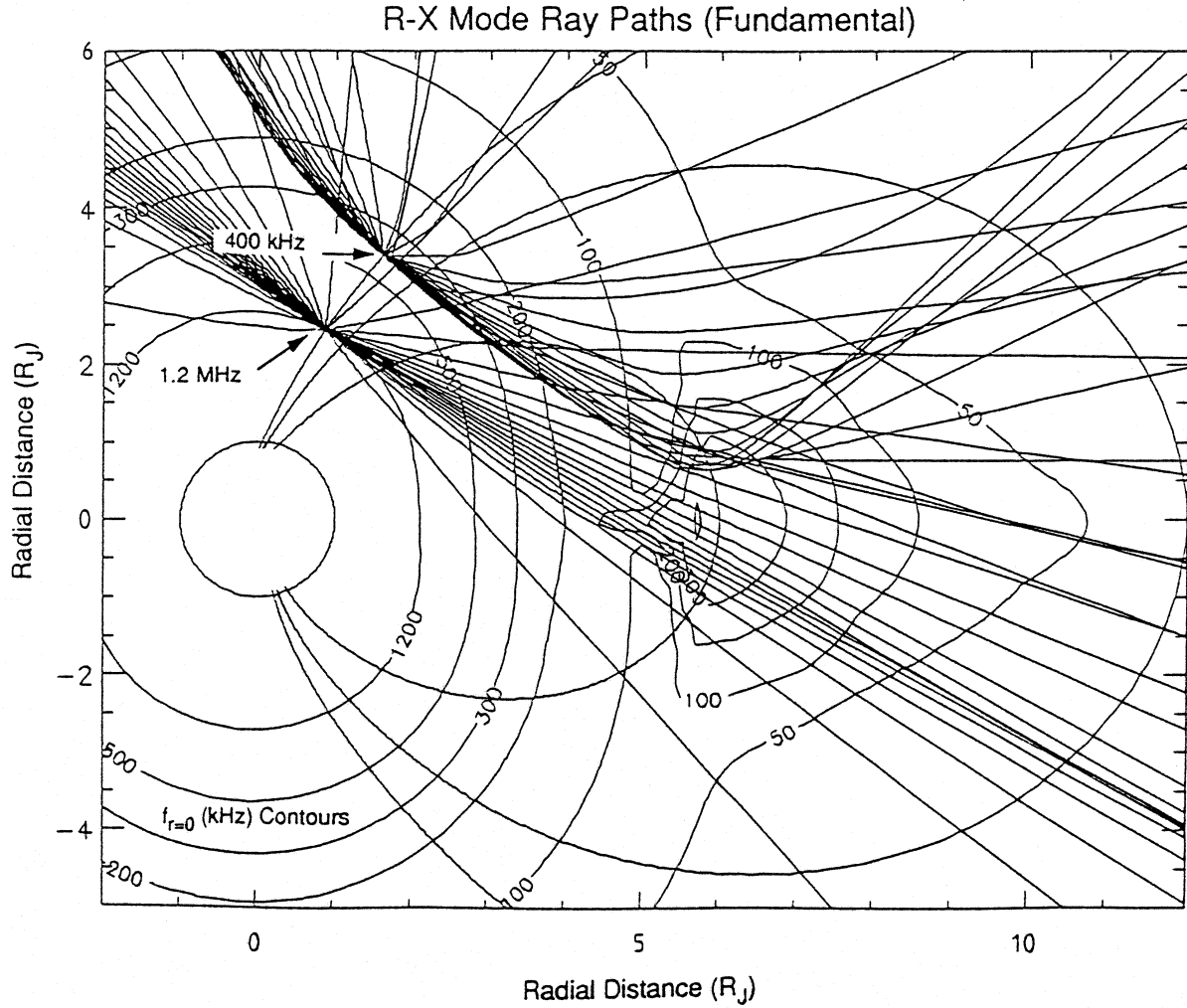


Figure 5: Three-dimensional HOM ray paths are projected into a meridian plane near the longitude of the assumed source region. Emission cones are shown for frequencies of 400 kHz and 1.2 MHz generated at the fundamental of the local electron gyrofrequency. The background of this figure contains contours of R–X cutoff frequency (in kHz) from the plasma models of the Jovian inner magnetosphere, including the Io torus, and magnetic field lines at L values of 6, 12, and 20. The Io torus provides a major source of refraction, for ray paths with frequencies < 800 kHz (clearly illustrated at 400 kHz). The torus becomes increasingly transparent at frequencies higher than 800 kHz (clearly illustrated at 1.2 MHz).

- R–X mode ray paths at HOM frequencies are not able to propagate over the Jovian magnetic pole to reach the low magnetic latitudes of $\pm 10^\circ$.
- Although the Io torus is potentially a major source of refraction, it is transparent to frequencies greater than about 800 kHz. Note the strong refraction of the 400 kHz rays that are intercepted by the torus. The rays that are in or near the meridian plane are refracted up toward high magnetic latitudes. The rays that are out of the meridian plane exit the torus parallel to the magnetic equator, while some can go below the equator.

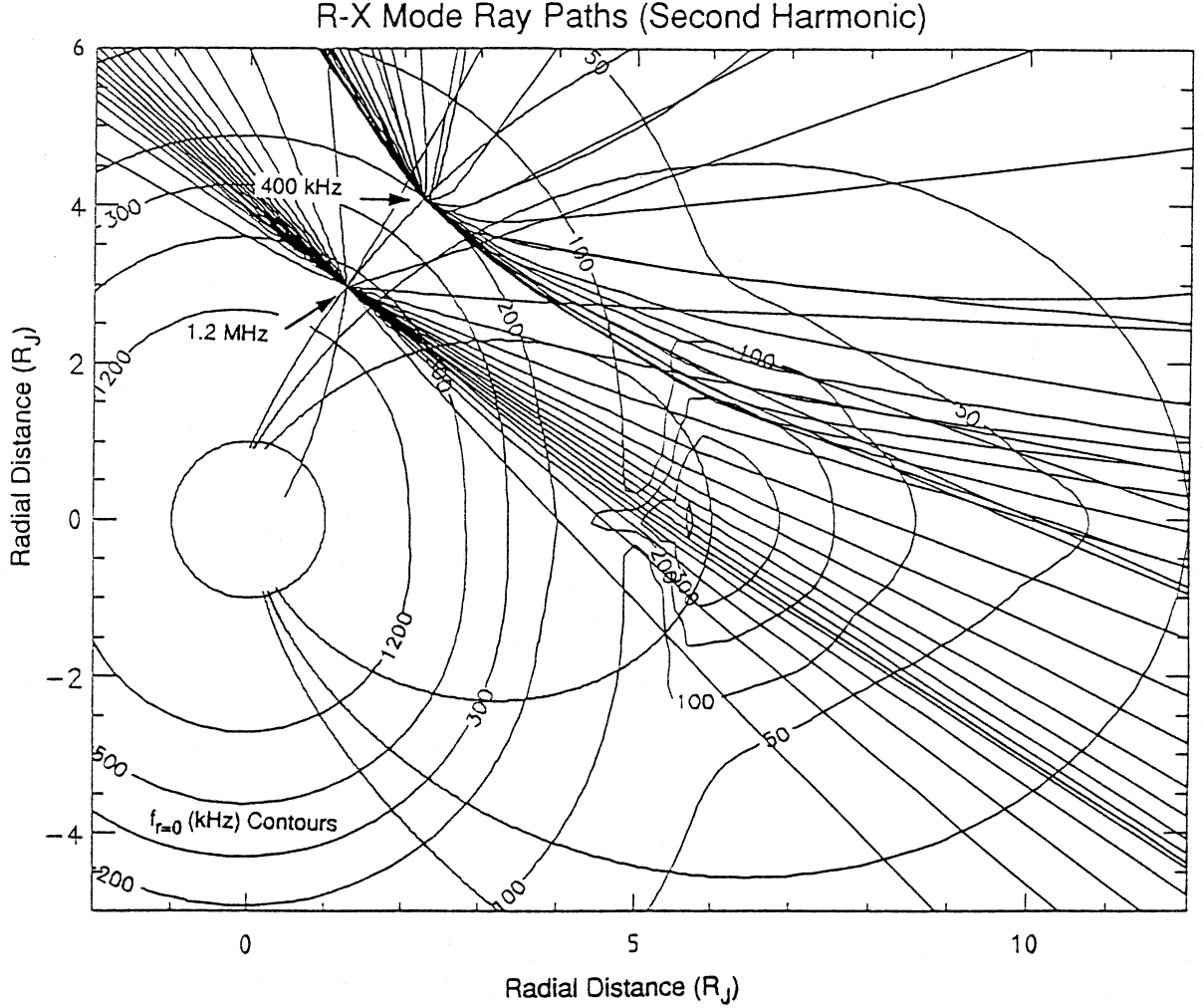


Figure 6: This figure has the same format as Figure 5 with the exception that the ray path calculations are started from a potential HOM source region where the wave frequency is twice that of the local electron gyrofrequency (second harmonic source region).

- In the case of the CMI emission mechanism with sources at $L=20$, the large initial wave normal angle of 85° produces emission cones which extend to more than 10° away from the magnetic equator for the higher wave frequencies (as shown at 1.2 MHz).

Figure 6 has the same format as Figure 5 with the exception that these ray paths are plotted from potential HOM sources which would generate emissions at the second harmonic of the local electron gyrofrequency. These ray paths are also generated with initial wave normal angles of 85° and exhibit many of the same characteristics as discussed in Figure 5 above. The most important difference between the fundamental and the second harmonic emissions is that the latitudinal extent of the rays is greater for the second harmonic emissions. This results from the fact that the second harmonic emissions are generated from higher up on the magnetic field lines where the curvature of the field towards the magnetic equator is greater, pointing the rays further south.

4 Discussion

From the ray tracing calculations, it is clear that the HOM source regions at longitudes 180° away from the observer (at the magnetic latitude of the Voyager spacecraft) cannot contribute to HOM emission observed. This implies that the lane features observed at a specific CML must be an effect which involves source regions having similar longitudes relative to the observer. The ray tracing calculations model reasonably well the effects of the HOM emissions at frequencies less than the lane frequencies. That is, the lower frequencies (from the same hemisphere source regions) are observed at typically higher magnetic latitudes than the high frequencies due to the refraction effects of the Io torus on the lower frequencies. This situation is further supported by the polarization measurements of Ortega-Molina and Lecacheux [1991] who found that the polarization of HOM is more strongly right hand polarized in the northern hemisphere with increasing magnetic latitude. The lane features at the upper end of the HOM frequency range may not be an effect of refraction by the Io torus since the modelled plasma density in the torus is not large enough to alter ray paths for those frequencies.

Based on the assumptions of large initial wave normal angles (85°) and a source location on a $L=20$ magnetic field line as in Ladreiter and Leblanc [1990a,b], our ray tracing calculations at high frequencies (see 1.2 MHz ray paths in Figure 5) indicate that the high frequency rays are beamed to much larger values of magnetic latitude than $\pm 10^\circ$ as concluded by Ladreiter and Leblanc. Possible resolutions to these differences may be in that a higher latitude source location or smaller initial wave normal angle should be chosen. It is important to note that the ray tracing calculations presented should only be interpreted qualitatively since the HOM source region proposed (at low altitudes and high magnetic latitudes) depends on the accuracy of the magnetic field and plasma model used. In addition, small changes in the initial wave normal angles or small changes in the L value of the source region (greater than 20) can lead to significant changes in the latitudinal extent of the rays.

In an effort to explore the possibility that second harmonic emissions generated by the CMI mechanism may explain the HOM propagation characteristics at high frequencies, Figure 7 has been adopted from Melrose et al., [1984] and is a plot of the normalized growth rate versus the ratio of the local electron plasma frequency and electron gyrofrequency. Figure 8 is a contour plot of the ratio of the local electron plasma frequency and electron gyrofrequency for the model Jovian magnetosphere used in this study. It is important to note that the potential sources for the fundamental and the second harmonic emissions are located in regions where the ω_p/ω_{ce} ratio varies from 0.015 to 0.03. Using this ratio of ω_p/ω_{ce} determined from Figure 8, Figure 7 shows that the second harmonic emissions in the X-mode should be at least two orders of magnitude less intense than the fundamental. An examination of Figure 1 clearly shows no diminutions of HOM emissions at the high frequencies. Therefore these emissions are probably not second harmonic.

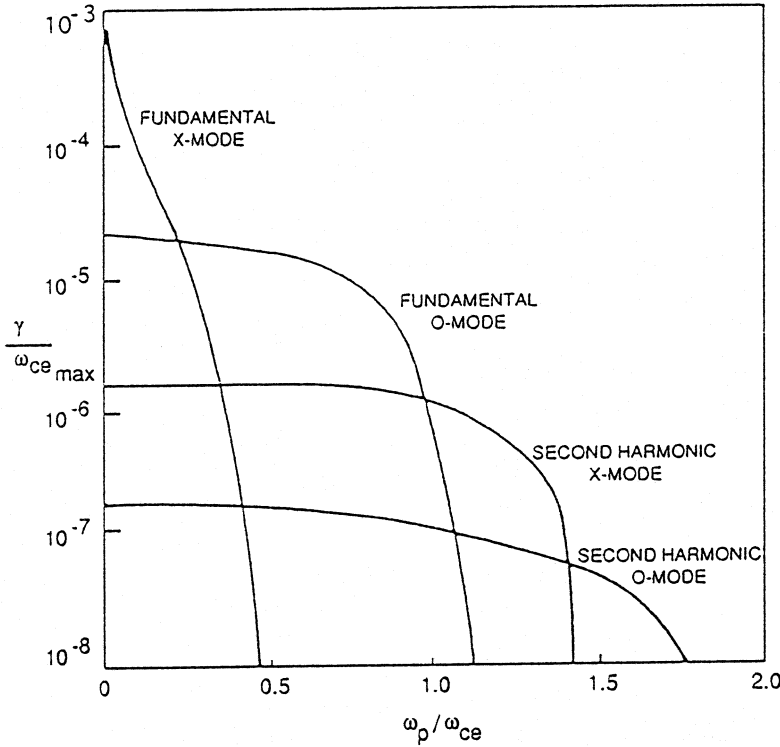


Figure 7: A plot of the normalized growth rate versus the local electron plasma frequency and electron gyrofrequency ratio (adopted from Melrose et al. [1984]). This plot shows that the second harmonic emissions in the X-mode are several orders of magnitude less intense than the fundamental for $\omega_p/\omega_{ce} \ll 1$.

5 Conclusions

The occurrence probability technique has illustrated a new and yet undiscovered feature of the Jovian HOM emissions. This technique is used to eliminate any effect that would be caused by the variable intensity of the HOM emission. A ‘lane’ of low emission probability appears in the HOM occurrence probability spectrograms of frequency versus System III longitude (CML). It has been determined that these lanes are observed repeatedly when the Voyager 2 spacecraft is between CML 70° to 130° and for the CML range of 265° to 335° . The lane feature is clearly shown in the HOM occurrence probability spectrograms of magnetic latitude versus frequency. The lane feature starts at $+10^\circ$ magnetic latitude at low frequency and extends down to the magnetic equator for HOM frequencies greater than 1 MHz. This analysis indicates that these lanes are permanent features (as observed by the inbound Voyager 2 spacecraft) and are not ‘drifting’ in longitude with time.

The lane feature may be interpreted as a persistent break in the overlap of the HOM northern and southern emission cones and is a function of frequency of the emission. This can be verified by studying the polarization signature across the lane features. Assuming the Io torus plasma model is accurate, the torus provides a major source of refraction at low HOM frequencies (below 800 kHz), but a cause for any refraction at the upper frequencies is still a mystery. Preliminary ray tracing calculations and the CMI growth rate considerations results indicate that HOM emissions at the second harmonic of the local electron gyrofrequency do not appear to contribute to the lane events.

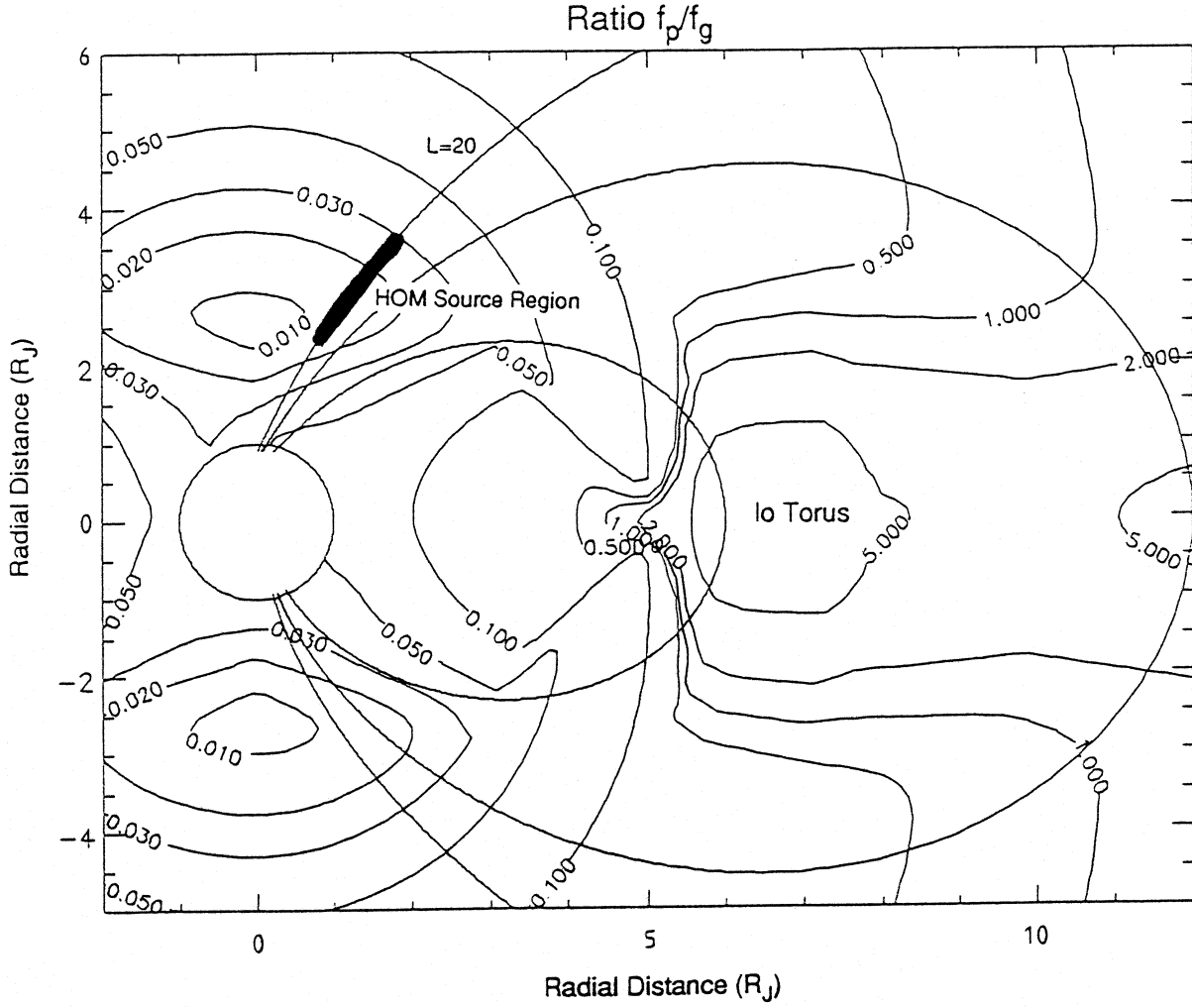


Figure 8: A contour plot of the local electron plasma frequency to electron gyrofrequency ratio for the model Jovian magnetosphere used in this study. It is important to note that the source regions for the R-X fundamental and the second harmonic emissions are located in regions where $\omega_p/\omega_{ce} \ll 1$.

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