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Second harmonic hectometric radio emission at Jupiter

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Abstract. Galileo has been in orbit around Jupiter since December 1995. The plasma wave instrument on board the spacecraft has occasionally detected a rotationally modulated attenuation band in the hectometric (HOM) emission that most likely is due to scattering of the radiation from density fluctuations along the Io L-shell, as reported earlier [cf. Gurnett et al., 1998]. The occurrence of the attenuation band is likely to be dependent on Io activity and the presence of density scattering centers along the Io L-shell as well as the location of the source region. Some of the attenuation bands show clear indications of second harmonic emission. Without polarization measurements, it is difficult to place constraints on the local generation conditions based on the cyclotron maser instability, but the results imply that second harmonic emission could be present in the decametric (DAM) radiation as well. A survey of the data has revealed about 30 examples of second harmonic HOM.

1.0 Introduction

1.1 HOM

Jovian hectometric (HOM) radio emissions are generally described as emissions in the frequency range of ~ 200 kHz to ~ 3 MHz (cf. Carr et al. [1983] and Ladreiter and Leblanc [1991]). Polarization measurements [cf. Reiner et al., 1993a] show a dominant X-mode. The source mechanism is most likely the cyclotron maser instability and the source region has been thought to be at L-shells higher than L = 6.

Using data from the Unified Radio Astronomy Instrument (URAP) on board the Ulysses spacecraft as it flew past Jupiter, Reiner et al. [1993a] found distinct northern and southern Jovian HOM emission and temporal variations within the emission on the order of 30 minutes. Using direction finding methods based on signal phase differences between antennas, Reiner et al. [1993a] found HOM sources to be located on L-shells of approximately 4-6, with beam opening angles from 10 - 50 degrees. This provided the first direct evidence for HOM source locations, and contradicted the belief by many that HOM was generated at high L-shells (L=20-30) in association with the solar wind (see Ladreiter and Leblanc [1989, 1990, 1991]). Subsequently Ladreiter et al. [1994] performed an analysis of the Ulysses plasma wave data including the effects of systematic errors due to antenna/receiver calibration uncertainties. These authors found HOM source regions most likely located along auroral zone L-shells in the range 7 < L < 11. Menietti and Reiner [1996] followed up on the results of Reiner et al. [1993a,b] by performing ray tracing of HOM emissions using Ulysses radio emission wave normal angles as a constraint. While the latter found source locations consistent with the range of magnetic L-shells in the range 3 < L < 7, they clearly saw the effects of wave refraction in the Io torus and suggested dynamic effects not explainable by a static torus density model.

1.2 Lanes in HOM Emission

The Voyager 1 and 2 spacecraft flew past Jupiter in March 1979 and July 1980 respectively, but measurements of the radio emissions from the planet by the Planetary Radio Astronomy (PRA) experiment were made for long periods before and after these encounters. Green et al. [1992] analyzed these data using an occurrence probability technique which enhanced any long term stable structure apparent in spectrograms of frequency vs. central meridian longitude. They noted the presence of persistent low-occurrence probability features which were labeled "lanes" since they appeared as linear decreases in emission probability in the midst of surrounding high probability amorphous emission. These features had been apparent in initial occurrence probability analyses of the Voyager data [Alexander et al., 1981], but had not been noted or studied at that time. In addition, Lecacheux et al. [1980] reported a "drifting gap in the main late source". Higgins et al. [1995] expanded the work of Green et al. [1992] by examining more cases and noting a possible relationship of the lanes to magnetic latitude and system III longitude, but no theory was presented to explain them.

1.3 Recent Galileo Results

Recently, Gurnett et al. [1998] have identified and explained a well-defined attenuation band modulated by the rotation of Jupiter. This attenuation band occurs in the Jovian hectometric and lower- frequency decametric radiation data from Galileo, and is apparently related to the "lanes" reported by Green et al. [1992] and Higgins et al. [1995]. The center frequency varies systematically with the rotation of Jupiter and has two peaks per rotation. It is believed that the attenuation occurs as the ray path from a high-latitude cyclotron maser source passes approximately parallel to the magnetic field near the northern or southern edges of the Io L-shell. Emission that is tangent to the Io L-shell can be scattered by density fluctuations or reflected at near grazing incidence (see Figure 1). The attenuation band peaks in frequency near 50 degrees CML due to sources of HOM in the southern hemisphere, and it peaks near 185 degrees due to sources in the northern hemisphere. Thus this attenuation band has aided in understanding the source location of the HOM emission. Another result of the observations of Gurnett et al. [1998] is that clear indications of second harmonic radio emission in the HOM and the low-frequency DAM emission have been identified. These results suggest that second harmonic emission is likely for higher frequencies as well.

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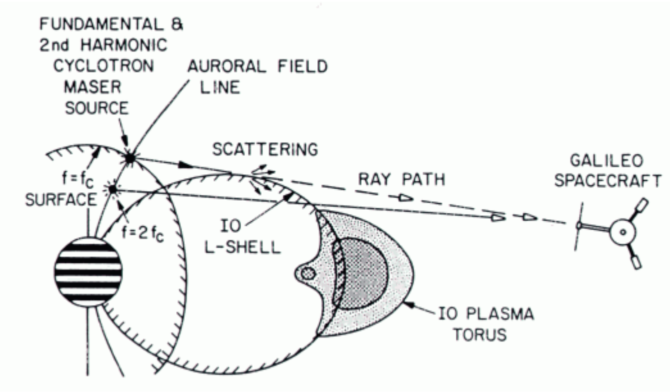

Figure 1. A model that attributes the attenuation to scattering or shallow-angle reflections in the region where the ray path is nearly tangent to the Io L-shell. The source region for both fundamental and second harmonic sources is seen.

1.4 Harmonic DAM/HOM

As predicted by the theory of the cyclotron maser instability (CMI), fundamental X-mode gyroemission is dominant over second harmonic X-mode for ratios of electron plasma frequency to gyrofrequency, $f_p/f_g < 0.3$, and free-energy electron energies $E > 2$ keV (we call this case A); fundamental O-mode and second harmonic X-mode emissions are dominant over fundamental X-mode emission for $0.3 < f_p/f_g < 1.0$ and $E > 2$ keV (we call this case B) [cf. Wong et al., 1982; Winglee, 1985]. Wong et al. [1989] have extended the theory of the CMI by demonstrating the importance of the energy dependence of the electrons providing the free energy for wave generation. They find that the energy of these electrons can play a significant role in determining the dominant wave mode. The temporal and spatial growth rates of both the fundamental O-mode as well as the second harmonic X-mode remain high for relatively low energies (several hundred electron volts) of the suprathermal electrons, while the fundamental X-mode is suppressed for energies of about 1 keV due to the relativistic resonance conditions. This result was found to be true even if the ratio f_p/f_g is < 0.3. It is possible that both second harmonic and fundamental O-mode emission may dominate over fundamental X-mode gyroemission if the energy of the particles supplying the free energy is less than about 2 keV. If this is the case, then we may expect to see, in the absence of fundamental X-mode, fundamental O-mode and second harmonic X-mode emission is generated along the same field line.

Menietti and Curran [1990] and Menietti [1995], using the Voyager 1 and 2 planetary radio astronomy radio emission data, have found examples of DAM that may be due to second harmonic gyroemission, as well as emission that may be due to mechanisms other than the cyclotron maser instability. The morphology of these putative second harmonic DAM emissions is similar to terrestrial second harmonic auroral kilometric

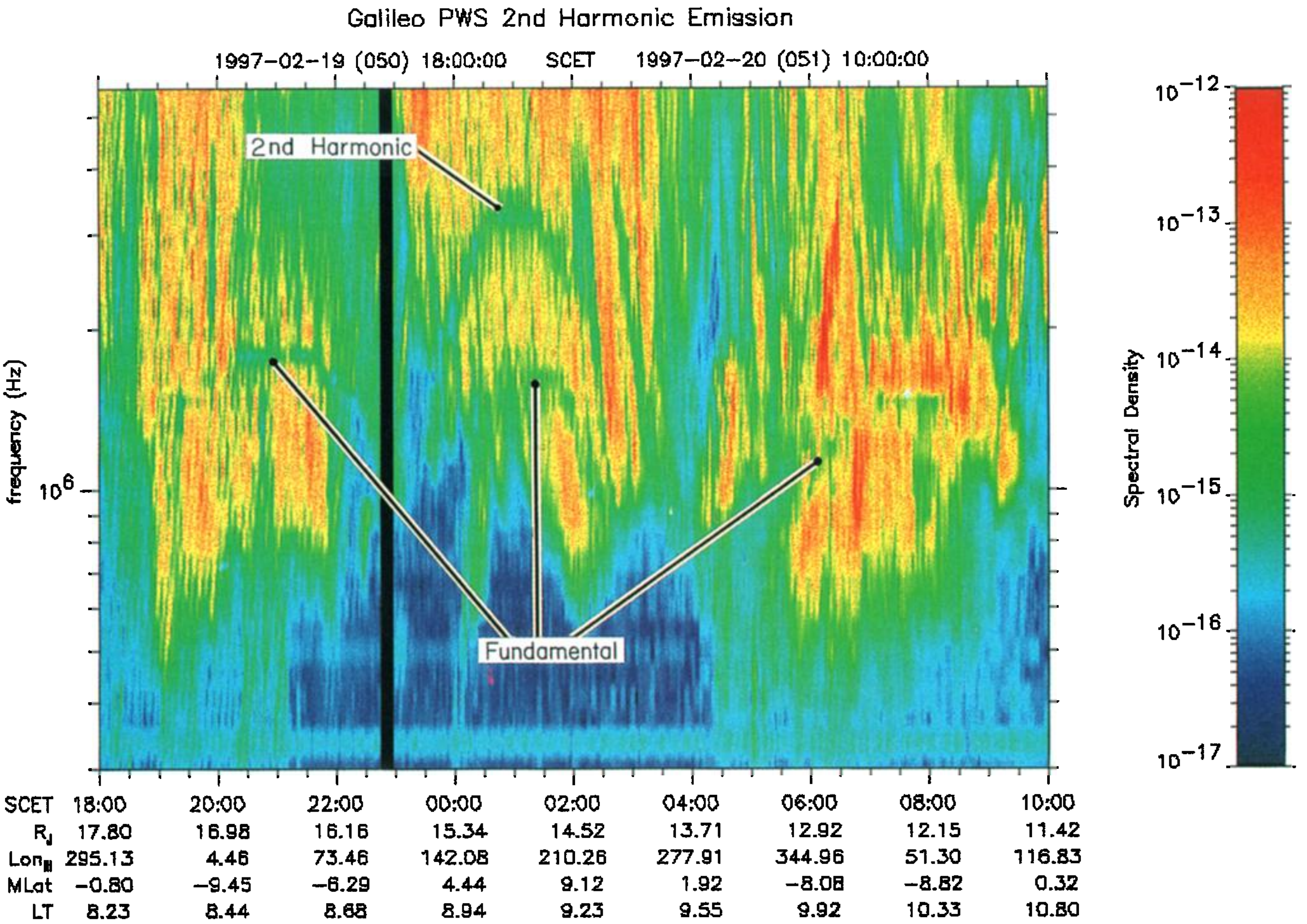

Figure 2. A frequency-time spectrogram showing the attenuation band observed in the Jovian hectometric radio emission spectrum for both fundamental and second harmonic gyroemission. The spectral density units are $V^2/(m^2\text{-Hz})$.

radiation reported by Mellott et al. [1986], however, the polarizations of the Jovian emissions, and hence the wave modes, were not determined. Observations of the Galileo plasma wave instrument reported here clearly indicate the presence of second harmonic HOM emission.

2.0 Instrumentation

The plasma wave receiver on board Galileo consists of 4 different swept-frequency receivers that cover the frequency range from 5.6 Hz-5.6 MHz for electric fields and 5.6 Hz to 160 kHz for magnetic fields. We will concentrate in this study on the electric fields obtained by the high-frequency receiver (HFR), which covers the frequency range from 100.8 kHz 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 seconds with a frequency resolution of about 10% [cf. Gurnett et al., 1992].

3.0 Observations

In Figure 2 we display a frequency-vs-time spectrogram of the plasma wave data obtained by the HFR on board the Galileo spacecraft. The data were collected on days 50 and 51 of 1997 while the spacecraft was near and within the orbit of Ganymede. The frequency range shown is from 100 kHz to 5.6 MHz. Indicated on the plot between about 19 hours, day 50 and 9.5 hours, day 51 and in the frequency range of about 900 kHz to nearly 4 MHz are attenuation band signatures of the type discussed in Gurnett et al. [1998]. Clearly seen for this example, however, is the harmonic nature of the attenuation band between about 23 hours, day 50 and 3.5 hours of day 51. Since the signature is an attenuation band, an instrumental source due to possible instrument saturation is not possible. The signatures are due to natural causes, and, based on the model presented in Gurnett et al. [1998], the cause of the harmonic signature is emission scattering within the Io torus L-shell of a high-latitude gyroresonant source near Jupiter. This scenario, including the second harmonic source, is diagrammed in Figure 1.

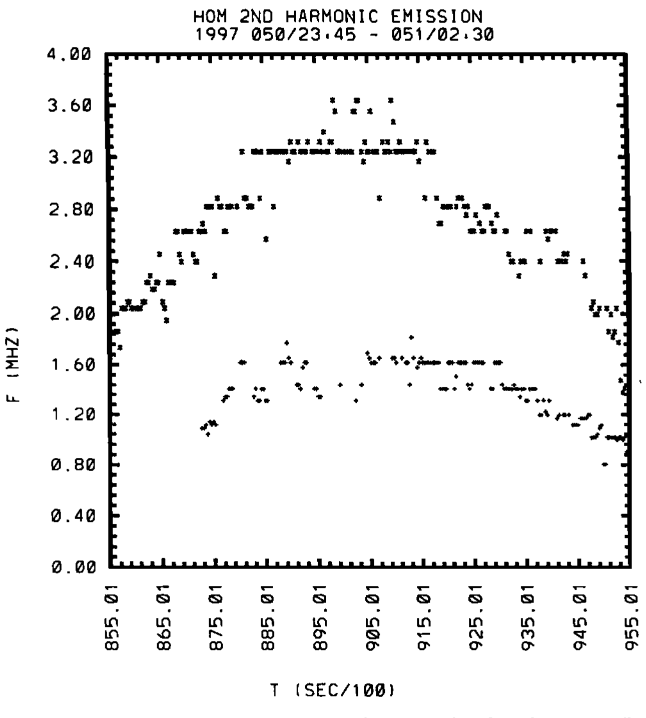

Figure 3. A linear plot of measured attenuation band centers (in frequency) versus time for both the fundamental and second harmonic HOM emission.

For clarity, in Figure 3 we have plotted, on a linear scale, the measured frequency of the center of the attenuation band versus time for both the fundamental and the second harmonic emission. The center of the bands was determined by careful examination of plots of power spectral density versus frequency over the range of times indicated. These plots are generated for each frequency cycle, thus every 18 2/3 seconds. As can be seen, despite the noise of the measurements, the second band of attenuation is typically at twice the frequency of the fundamental band.

We have examined the Galileo radio emission data from day 341 of 1995 until day 100 of 1998 for other examples of second harmonic emission. We have tabulated about 30 examples of second harmonic emission similar to Figure 2. The examples are confined to radial distances of about 130 Jovian radii (R_J), and thus are restricted by the orbit to lie in the local time range from about 8 hours to about 18 hours.

4.0 Summary and Discussion

We have shown an example of both fundamental and harmonic hectometric radiation at Jupiter as identified from rotationally modulated attenuation lanes. As first described in Gurnett et al. [1998] these attenuation bands are most likely due to HOM radio emission from discrete source regions that is scattered when it propagates nearly tangent to the magnetic field line that intercepts Io's orbit (Figure 1). As described above, according to the cyclotron maser instability, second harmonic radio emission is possible for a combination of conditions near the source region. Figure 2 indicates that the depth of the attenuation bands for both the fundamental and second harmonic emission are similar, but the second harmonic lanes are somewhat more attenuated. Based on the power levels of the emission adjacent to the attenuation bands, we postulate that the intensity levels of the fundamental and second harmonic emission are comparable. To date, observations of HOM have been predominately X-mode [cf. Reiner et al., 1993a,b]. Assuming that is the case here and assuming a low density plasma, then according to the theory of the CMI outlined above, a source region with plasma conditions intermediate between case A and case B could apply, with plasma energies $E > 2$ keV and $f_p/f_g < 0.3$. However, if the fundamental emission is O-mode, then the ratio of f_p/f_g in the source region depends upon the free energy of the electrons. Without polarization measurements, it is impossible to determine the mode of the HOM emissions, which, in turn, would provide more constraints on the plasma conditions in the generation region.

The relative scarcity of observations of second harmonic emission bands has at least two explanations. First, fundamental gyroemission from a source with a frequency equal to that of the second harmonic gyroemission occurs at smaller radial distances along the magnetic field line (see figure 1), and in general would "fill in" the emission attenuated from the second harmonic source. Secondly, as commented by Gurnett et al. [1998], the occurrence of attenuation bands is more common at radial distances of less than about 50 R_J. This is likely due to lower intensity levels of the radio signal and increased scattering of the HOM emission (increased signal to noise ratio) at larger distances. A third reason for the absence of HOM attenuation bands might be the absence of HOM sources along magnetic field lines with $L > 6$.

Finally, the observations of second harmonic HOM reported here lend additional credence to the reports of possible Jovian second harmonic decametric emission [cf. Menietti and Curran, 1990]. The presence of such emission provides more insight into the plasma processes in the near-Jupiter magnetosphere. It will be interesting to look for other such attenuation bands in future planetary data.

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