Possible eigenmode trapping in density enhancements in Saturn's inner magnetosphere

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[1] We report a re-examination of observations of radio waves and banded fine structure observed by Cassini in the Saturn inner magnetosphere. These emissions have been identified in the past as Z-mode emission from possible density cavities along the inner edge of the Saturn plasma torus. A careful examination of the emission fine structure in a region where the ratio of plasma to cyclotron frequency $f_p/f_{ce} < 1$ suggests that the emission bands may be due to eigenmode trapping from density enhancement source regions. The observations are similar to those made at both the Earth and Jupiter and suggest that radio emission fine structure is a remote diagnostic of density fluctuations in planetary magnetospheres. **Citation:** Menietti, J. D., P. H. Yoon, and D. A. Gurnett (2007), Possible eigenmode trapping in density enhancements in Saturn's inner magnetosphere, *Geophys. Res. Lett.*, *34*, L04103, doi:10.1029/2006GL028647.

1. Introduction

[2] On July 1, 2004, during the orbit insertion, the Cassini spacecraft made a pass in to a radial distance of less than 2.0 R_S (Saturnian radii) from Saturn. Data were successfully acquired during the entire inbound pass through a cold plasma torus, and through the region inside the cold torus to a radial distance of $\sim$1.4 R_S. The purpose of this paper is to re-analyze the results obtained from the plasma wave investigation during this pass, in light of recent observations of fine structure observed in terrestrial continuum emission.

[3] As reported by *Farrell et al.* [2005] during this orbit and closest approach to Saturn a set of narrow bandwidth tones or emissions were observed by the Radio and Plasma Wave Science (RPWS) instrument [cf. *Gurnett et al.*, 2004]. These emissions were observed inside the inner edge of the plasma torus ($r \lesssim 2.5$ R_S) that has been reported [cf. *Richardson and Jurac*, 2004]. The emission bands lie in the range from 3 to 70 kHz with bandwidths as low as a few hundred hertz. The tones lasted up to an hour in some cases. *Farrell et al.* [2005] have presented arguments for interpreting these tonal emissions as narrowband Z-mode emission emanating from electrostatic f_p plasma oscillations associated with density cavities near the torus via wave conversion.

[4] These Saturnian tones or emission bands are quite similar to those observed at Jupiter by the Galileo spacecraft during its trajectory into the region inside the inner edge of the Io plasma torus on orbit A34. The Galileo 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 showed an array of emission bands. 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. *Menietti et al.* [2005a] reported the emission bands existed below frequencies of 100 kHz in frequency intervals that vary from a few hundred Hz to several kHz. The emission mode was found to be consistent with both O- and Z- mode. Emission bands at Jupiter for $f < 5$ kHz were noted to be similar to terrestrial continuum emission bands associated with $(n + {}^1\!/_2)$ harmonics of the electron cyclotron frequency, f_{ce} [cf. *Kurth*, 1982].

[5] *Menietti et al.* [2003, 2005b] reported terrestrial observations of fine structure associated with continuum and kilometric continuum radio emissions observed by the Polar and Cluster spacecraft. It was suggested by these authors that such fine structure could result from density fluctuations or cavities in the plasmasphere or plasmapause region. *Samara et al.* [2004] have reported fine structure emission bands associated with upper hybrid waves that are attributed to eigenmodes trapped within a density enhancement. These observations were obtained by the High Bandwidth Auroral Rocket (HIBAR) sounding rocket in the pre-midnight auroral region and near a density shoulder. *Yoon and LaBelle* [2005] and *Yoon and Menietti* [2005] carried out eigenvalue analysis for upper-hybrid/Langmuir waves trapped in cylindrical density structures of the terrestrial plasmapause region. The method of the analysis is similar to that considered by *McAdams et al.* [2000] who emphasized the quasi-parallel trapped Langmuir waves, and by *Yoon et al.* [2000] who paid special attention to upper-hybrid waves trapped in a density enhancement. Using physical parameters typical of a kilometric continuum (KC) source region, *Yoon and Menietti* [2005] found that the frequency spacing between individual fine structures are within a reasonable observed range of 0.1 – 1 kHz. Quasi field-aligned modes are associated with density cavities, while the radial modes are excited within an enhanced density column, thus showing that density irregularities of various types can support discrete wave spectra featuring wide-ranging frequency gaps. *Menietti and Yoon* [2006] have subsequently presented observations of plasma waves in the nightside terrestrial plasmapause that appear to be generated and at least partially trapped in a density cavity. These latter authors concluded that the wave fine structure can be explained by eigenmode analysis and is a diagnostic of small scale density fluctuations perhaps embedded within larger scale structures. The density cavities appear to be

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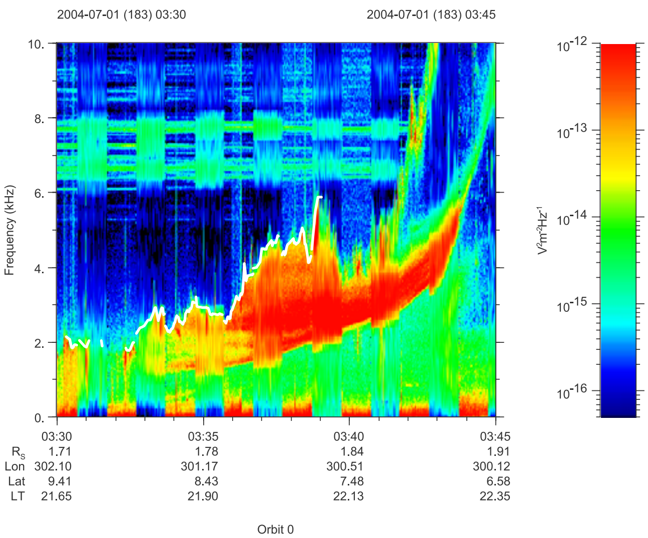

Figure 1. High resolution wideband data for July 1, 2004, obtained by the radio plasma wave instrument (RPWS) on board the Cassini spacecraft. Seen in the frequency-time spectrogram of electric field intensity are narrowband emissions from sources probably associated with density enhancements.

sources of continuum and kilometric continuum emission. That is, these cavities are sources of Langmuir/Z-mode emission which can mode convert to free space O-mode emission as described by *Yoon et al.* [1998], *Yoon and LaBelle* [2005], and *Yoon and Menietti* [2005].

[6] The observations reported by *Farrell et al.* [2005] may be a result of eignenmode trapping in density structures associated with the inner edge region of the Saturn density torus. In this paper we re-examine the radio emission data for the Saturn injection orbit and attempt to determine the mode and source of the emission, relating it to the work on eigenmode analysis described above.

2. Observations

[7] The data presented by *Farrell et al.* [2005] have been re-processed at highest resolution and show indications of fine structure as observed at Earth for continuum emission and at Jupiter for orbit A34 when Galileo flew inside the inner radius of the Io plasma torus.

[8] In Figure 1 we present high resolution wideband data obtained by the radio plasma wave instrument (RPWS) on board the Cassini spacecraft on July 1, 2004. Seen in the frequency-time spectrogram of electric field intensity are emissions previously identified by *Xin et al.* [2006] as whistler mode with a source possibly above the rings of Saturn. This emission is thus used to identify the plasma frequency as shown in Figure 1 by the white line. Figure 1 is generated using the combined data from the receiver during a time period when the bandwidth was alternately selected every 60 seconds between 10 kHz and 80 kHz. This explains the vertical striping on the plot. In the frequency range above about 5000 Hz we observe emission bands or tones previously identified by *Farrell et al.* [2005] as propagating in the Z-mode. These emissions propagate above the local plasma frequency, indicated in Figure 1 by the white line, and well below the electron cyclotron frequency, which is about 90 kHz at this time. As suggested by *Farrell et al.* [2005] these bands could be generated by plasma oscillations due to density fluctuations. In this theory the electrostatic plasma oscillations are associated with density cavities. The emission is thought to propagate into regions of higher density where a mode conversion to Z-mode is likely. The source of the plasma oscillations was identified by *Farrell et al.* [2005] as the inner edge of the Saturn plasma torus which is located at about $r = 2.2\ R_S$.

[9] In Figure 1 there is an indication of a fine structure to the bands or tones identified by *Farrell et al.* [2005]. In Figure 2 we focus on the emission bands in the frequency range from 4 to 12 kHz. We see that the emission bands are actually composed of closely-spaced fine structure. These emission bands resemble those identified by *Menietti and Yoon* [2006] associated with density structures in the terrestrial plasmapause. The spacing between the emission bands is $\Delta f \ll f_{ce}$, indicating that these emissions are not simply $(n + {}^1\!/_2)\ f_{ce}$ harmonic emissions that have been observed frequently in the past at the terrestrial magnetic equator. In analogy to the work of *Yoon and LaBelle* [2005], *Yoon and Menietti* [2005], and *Menietti and Yoon* [2006] we propose that these emissions have a source in regions of density fluctuation. The density fluctuations are near the plasma enhancement between 03:40 UT and 03:48 UT identified by *Xin et al.* [2006] associated with the Cassini division.

3. Discussion

[10] The observations reported by *Farrell et al.* [2005] when Cassini was inside the inner radius of the plasma torus at Saturn in many ways are similar to those observed by *Menietti et al.* [2005a] at Jupiter. In the work of *Farrell et al.* [2005, Figure 2] there are additional emission bands at

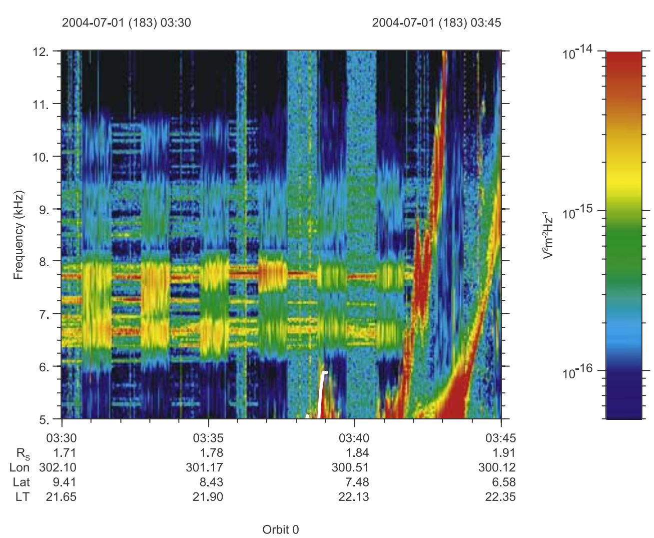

Figure 2. Emission bands in the frequency range from 5 to 12 kHz, seen at higher resolution than Figure 1. The bands are composed of closely-space fine structure with $\Delta f \ll f_{ce}$ and resembling those observed in the terrestrial plasmapause region associated with density structures.

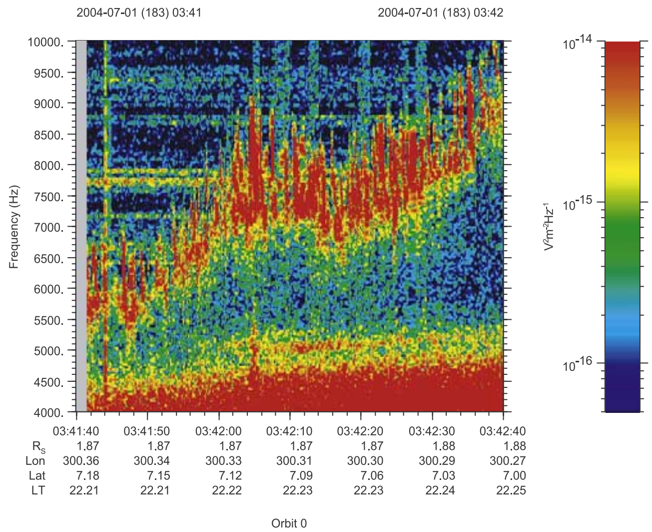

Figure 3. A frequency-vs-time spectrogram of 60 seconds of electric field intensity data starting at 03:41:40 UT in the frequency range from 4 kHz to 10 kHz. Note the broadbanded emission bursts possibly associated with density fluctuations.

higher frequency that the authors associated with possible sources along the inner edge of the Saturn torus. We suspect that these bands of emission at f > 10 kHz also show a fine structure as do those in Figure 2, however, the frequency resolution for f > 10 kHz is not sufficient to observe any fine structure. Based on the recent terrestrial results of *Yoon and LaBelle* [2005], and others cited above, we find that the emission bands observed at Jupiter and at Saturn as reported here and in the work of *Farrell et al.* [2005] may result from trapped eigenmodes within finite-sized density fluctuations (either cavities or enhancements). As *Yoon and Menietti* [2005] pointed out, quasi-parallel Langmuir/upper hybrid modes possess generally narrower frequency spacing and are associated with density cavities

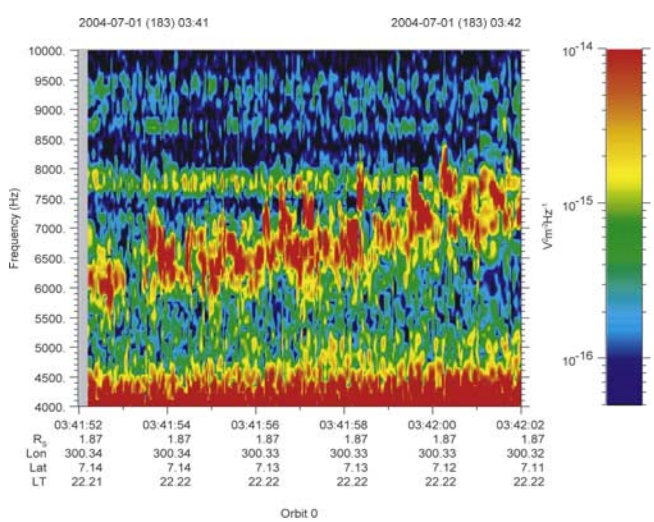

Figure 4. A 10-second sub-interval of Figure 3 starting at 03:41:52 UT. Note that most of these bursts have time extents that are much less than 1 second in duration.

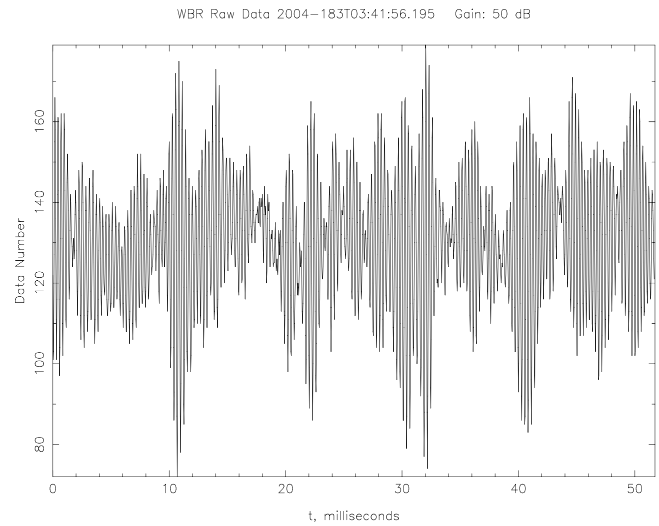

Figure 5. Waveform data during a short 52 ms time interval starting at 03:41:56.695 UT is shown. Note the series of wavepackets that can be less than 2 ms in time extent.

(for $f_p/f_{ce} > 1$), while quasi-perpendicular modes typically possess wider frequency gaps, and are associated with an enhanced density column (for $f_p/f_{ce} < 1$). In the case of the Saturn observations, $f_p/f_{ce} \ll 1$, so we would expect density enhancements as source regions.

[11] The relation between the frequency spacing of the fine structure and the local plasma parameters is given by *Yoon and Menietti* [2005, equation (7)]:

$$\Delta\omega = 2V_t \frac{\omega_p^2(0)}{\Omega^2}\sqrt{\frac{-n''(0)}{n(0)}} \qquad (1)$$

where V_t is the thermal velocity, $\omega_p(0)$ is the plasma frequency at the center of the density enhancement, $\Omega = 2\pi f_{ce}$ and $n(r) = n(0) + n''(0)r^2/2$ is the density radial profile of a cylindrical density fluctuation. We can make the approximation that $n''(0)/n(0) \sim 1/L^2$, where L is the radial extent of the density fluctuation perpendicular to B. For much of the time interval shown in Figure 1 we note that $f_p(0)/f_{ce} \sim 0.1$. We can also estimate V_t by assuming (as does *Farrell et al.* [2005]) a plasma temperature of 1 eV or $V_t \sim 4.19 \times 10^2$ km/sec, which then allows us to write $\Delta f \sim 1300/L$(m).

[12] We can make some estimates of L based on the size of the proposed source regions. In Figure 3 we plot 60 seconds of data starting at 03:41:40 UT in the frequency range from 4 kHz to 10 kHz, where we observe the broadbanded emission bursts possibly associated with density fluctuations. A 10-second sub-interval starting at 03:41:52 UT is re-plotted in Figure 4, where we can see that most of these bursts have time extents that are much less than 1 second in duration. The waveform data during a short time interval starting at 03:41:57 UT are shown in Figure 5, which displays a series of wavepackets that can be less than 2 ms in time extent. Each wavepacket likely corresponds to an independent burst of emission. For a spacecraft velocity of approximately 25 km/sec, a 2 ms encounter with a density

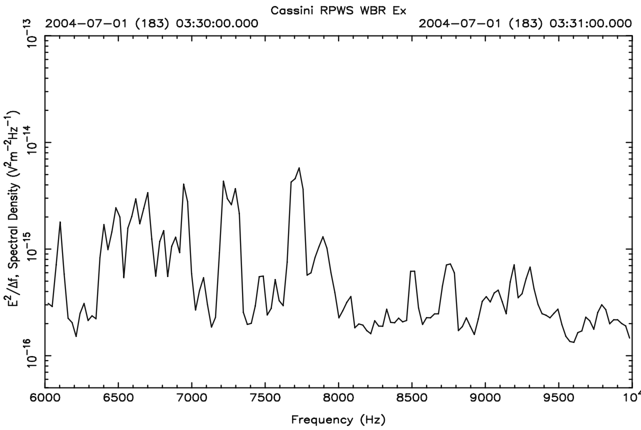

Figure 6. Power spectral density (V^2/m^2 – Hz) versus the wave frequency for the range 6 to 10 kHz in the time interval 03:30 UT to 03:31 UT. Fine structure peaks are separated typically by about 80–100 Hz in the frequency interval 6000 Hz < f < 7000 Hz.

fluctuation implies $L \sim 50$ m. Using equation (1) with L = 500 m yields $\Delta f \sim 30$ Hz, which is less than the nominal resolution of the wave receiver on board Cassini (~100 Hz). In Figure 6 we plot the power spectral density versus the frequency for the range 6 to 10 kHz in the time interval 03:30 UT to 03:31 UT. Here we see the fine structure with peaks separated by varying intervals, with a typical value of about 80–100 Hz in the frequency interval 6000 Hz < f < 7000 Hz. This must represent the maximum value of Δf since it is about the same as the resolution of the receiver. Using equation (1) with $\Delta f \sim 100$ Hz, we obtain $L \sim 10$ m. A smaller value of Δf would imply a larger density enhancement region as described by equation (1). Thus, we estimate that if the fine structure bands are produced by eigenmodes within density enhancements, these density structures have a typical dimension that is likely $L > 10$ m.

4. Summary and Conclusions

[13] We have presented observations of plasma waves that appear to be generated and at least partially trapped in density enhancements located near the Cassini division and inner edge of the Saturn plasma torus. *Farrell et al.* [2005] have reported the emissions are consistent with Z-mode possibly associated with electrostatic plasma oscillations in regions near and within density cavities with a density gradient parallel to the magnetic field, B. The fine structure present, however, is consistent with the theory of *Yoon et al.* [2000] and the observations of *Menietti and Yoon* [2006] which argue for density enhancements with density gradient perpendicular to B as source regions when $f_p/f_c < 1$ as is the case for the observations of Figure 1. Z-mode emission can be converted to O-mode near a density gradient [cf. *Horne*, 1989, 1990], so it is possible that some of the emission observed for $f > f_p$ is O-mode emission.

[14] *Xin et al.* [2006] have suggested that the density increase observed in Figure 1 just after 03:42 UT [see *Xin et al.*, 2006, Figure 4] is due to the plasma flowing freely through the Cassini division. The authors suggest that this region is also associated with a nearby field-aligned current similar to that observed in the terrestrial auroral region. The terrestrial auroral region is known to contain density structures that are the source of auroral roar fine structure that is proposed to be due to eigenmode trapping in density enhancements [cf. *McAdams and LaBelle*, 1999]. *Samara et al.* [2004] have presented similar terrestrial observations for the case of auroral roar detected by the HIBAR auroral rocket.

[15] We conclude that the wave fine structure can be explained by eigenmode trapping and is a diagnostic of small scale density fluctuations perhaps embedded within larger scale structures. The density enhancements appear to be sources of banded radio emission in a region of $f_p/f_{ce} < 1$. That is, these enhancements are sources of upper hybrid/Z-mode emission which can mode convert to free space O-mode emission. Such density structures are thus an important part of the inner magnetosphere of Saturn, particularly inside the inner edge of the Saturn plasma torus, and in regions above the ring plane associated with field-aligned currents.

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