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Plasma waves and fine structure emission bands within a plasmapause density cavity source region

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[1] We report observations of plasma waves and banded fine structure within a density cavity in the terrestrial nightside plasmapause. The observations were obtained by the wideband receiver of the plasma wave instrument on board the Polar spacecraft. We can identify Langmuir/upper hybrid emission and *Z*-mode emission within two distinct frequency zones of the density cavity source region. These observations appear to be consistent with eigenmode trapping of partially electrostatic waves. The plasma waves appear to be trapped within the density cavity bounded at low frequencies by the $L = 0$ surface. A second distinct region of plasma waves exists bounded at low frequencies by $f = f_{pe}$ (plasma frequency), but includes *Z*-mode at higher frequencies up to $f = f_{UH}$ (upper hybrid frequency). Intense fine structure emission bands are observed in both regions of the density cavity. We conclude that density cavities are an important source of plasma waves including continuum and kilometric continuum emission and the fine structure can be a remote diagnostic of density structures within the plasmapause/plasmasphere region. **Citation:** Menietti, J. D., and P. H. Yoon (2006), Plasma waves and fine structure emission bands within a plasmapause density cavity source region, *Geophys. Res. Lett.*, *33*, L15101, doi:10.1029/2005GL025610.

1. Introduction

[2] As reported by *Hashimoto et al.* [1999] kilometric continuum (KC) is emission that lies in the same frequency range as auroral kilometric radiation (AKR) [cf. *Gurnett*, 1974], but with a different spectral morphology and a unique source region. KC was observed by Geotail (in an equatorial orbit) to consist of slowly drifting narrowband signals in the frequency range 100 kHz $< f <$ 800 kHz. *Menietti et al.* [2003] reported high resolution observations made by the plasma wave instrument (PWI) on board the Polar spacecraft as it was passing through the source region of the KC emission in the plasmapause. High resolution wideband measurements indicated not just emission at f_{ce} and its $(n + 1/2)$ harmonics, but at frequencies separated in frequency by $f \ll f_{ce}$. These observations were consistent with electrostatic upper hybrid emissions as well as electromagnetic *Z* and ordinary mode waves. In addition, *Menietti et al.* [2005] have discussed Polar and Cluster observations of continuum emission fine structure. High resolution waveform data from Polar were used to directly measure the polarization of continuum emission and the direction of propagation. The authors found that the continuum emission at high resolution has a fine structure very similar to KC emission. One explanation for such emission is that it is due to multiple sources associated with density cavities and ducts which are present in the plasmasphere/plasmapause [e.g., *LeDocq et al.*, 1994; *Carpenter et al.*, 2002; *Darrouzet et al.*, 2002, 2004; *Fung et al.*, 2003; *Decreau et al.*, 2004]. *Green et al.* [2004] have shown that KC emission is often associated with a density depletion or notch structure in the plasmasphere.

[3] Eigenmode trapping of Langmuir/upper hybrid emissions for both density cavities and density enhancements [cf. *McAdams et al.*, 2000; *Yoon et al.*, 1998, 2000] has been suggested to explain discrete emissions (fine structure) of auroral roar. A modification of such processes will likely explain the plasmaspheric observations of continuum and kilometric continuum. *Yoon et al.* [1998] have shown that the growth rates of *Z*-mode are greatly enhanced when $f_{UH}^2 = (nf_{ce})^2$ where n = 2 and 3. This *Z*-mode can escape into free space by a linear mode conversion into *O* or whistler mode [e.g., *Jones*, 1982]. Recently, *Yoon and Menietti* [2005] have shown that eigenvalue analysis for upper-hybrid/Langmuir waves trapped in cylindrical structures (either density cavities or enhancements) lead to wave fine structure consistent with observations. Comparison with specific examples of KC indicates that a density cavity with a characteristic dimension perpendicular to the magnetic field of about 10 km could produce fine structure with spectral line separation similar to that observed.

[4] Observations of kilometric continuum and continuum emission associated with density structures at relatively high magnetic latitude have already been reported by *Menietti et al.* [2003, 2005] and *Decreau et al.* [2004]. In this paper we present observations of the Polar spacecraft that show direct evidence of a density cavity as the source of intense Langmuir and *Z*-mode emission consistent with the work of *Yoon and Menietti* [2005]. These observations suggest a new understanding of the source of continuum and KC emission in the plasmaspause region, and indicate that this region is highly inhomogeneous.

2. Observations

[5] In Figure 1 we display a frequency versus time spectrogram with electric field power gray-coded in units of $V^2\ m^{-2}\ Hz^{-1}$. This plot shows wave intensities for a southern hemisphere plasmapause/auroral region pass which occurs near the Polar spacecraft perigee. Identified on the plot are auroral kilometric radiation (AKR), auroral hiss, and upper hybrid band emission. The latter clearly

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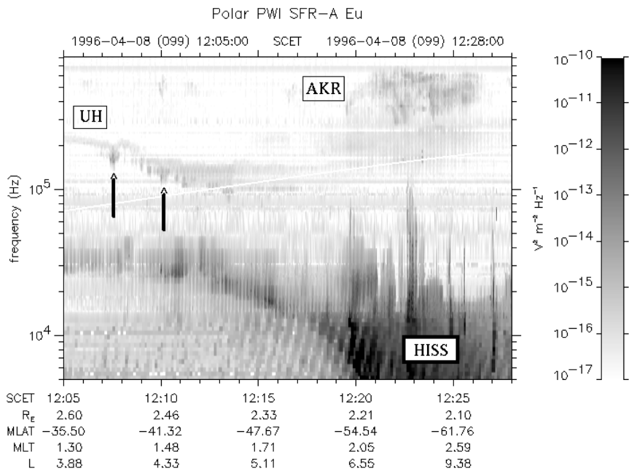

Figure 1. Frequency-time spectrogram for the Polar PWI sweep frequency receiver. The frequency range shown is from 5 kHz to over 800 kHz. The white line indicates the electron cyclotron frequency. The plot extends for 23 minutes as the spacecraft leaves the nightside plasmasphere and crosses the southern hemisphere auroral region.

shows a falling density as the spacecraft exits the plasmapause and enters the auroral region. The arrows indicate two periods of the upper hybrid band emission that appear unusual, that is, broadbanded. These structures are similar to those observed by *Menietti et al.* [2003] (cf. their Figure 4a). The wide band receiver (WBR) is a part of the PWI on board Polar. It was extremely fortunate that the WBR was operating and in precisely the correct mode to obtain excellent high resolution data for the event indicated by the first arrow as displayed in Figure 2a. This plot shows a spectrogram of wideband data over a 48-second period. The plot extends over a 90 kHz band of frequency extending from 125 kHz to 215 kHz. This plot is remarkable because it clearly shows that the period of interest actually is composed of two distinct frequency zones of emission. The emission lies within a density cavity as shown by the decreasing upper limit with a minimum frequency near 12:07:34. In addition, we observe a large number of emission bands each at nearly constant frequency. These fine structure lines appear to be enhanced and at least partially trapped in the lower frequency emission region, but can escape (extend beyond) the upper region. The fine structure bands occur from the lowest to the highest frequencies of emission. The most intense emission occurs in the approximate frequency range 153 kHz < f < 169 kHz. Careful examination of this more intense emission shows that it is temporally varying and bursty in nature. Examination of the raw data confirms that none of the emission saturates the receiver. The two emission bands indicated by arrows on the right side of Figure 2 are due to spacecraft interference.

[6] Spin modulation nulls are present on the plot approximately every 3 seconds (Polar has a spin rate of ~6 seconds). These modulation lanes provide some polarization information. Note that there is a phase difference of about 90 degrees between nulls of the lower-frequency zone emission and those of the lower boundary of the upper-frequency zone emission. At higher frequencies in the upper-frequency zone careful examination reveals that the more diffuse emission is in phase with that of the lower-frequency zone, while the discrete emission bands at highest frequency are out of phase by 90°.

[7] To identify the wave modes it is necessary to know the fundamental plasma cutoffs and resonances. We have used the angle between the electric field antenna and the local ambient magnetic field to assist in this identification. In Figure 2b the vertical white lines are located when this angle is near either zero or 180 degrees. From this it is clear that the emission in the lower region is peaked near 90°, while the emission at the lower boundary of the upper region is peaked near 0°. This strongly implies that this latter emission is likely Langmuir oscillations near the local plasma frequency.

[8] By assuming a value of f_{pe}, and knowing the magnitude of the local magnetic field (at 12:07:34, f_{ce} = 81.0 kHz), we identify the upper hybrid resonance frequency, f_{UH},

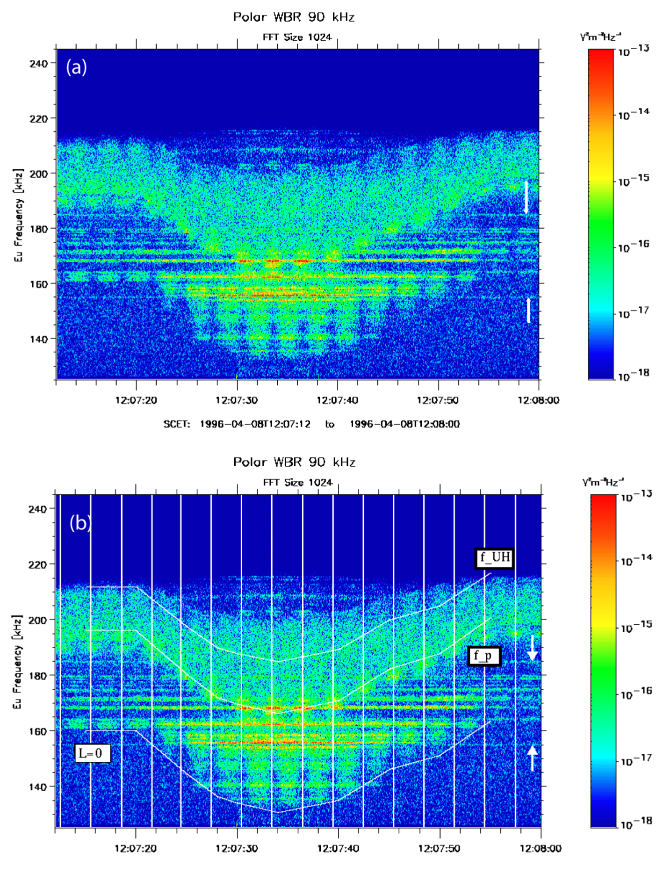

Figure 2. (a) A frequency-time spectrogram of the wideband receiver with electric field intensity color-coded. The frequency range is from 125 kHz to 245 kHz, but above 215 kHz there is a roll-off filter attenuating the data. The data show intense emission bands associated with two distinct frequency zones within a density cavity. (b) Same as Figure 2a but now with white lines indicating the upper hybrid frequency, plasma frequency, and the boundary surface at L = 0. The vertical white lines indicate times when the angle between the electric field antenna and the magnetic field was either zero or 180°.

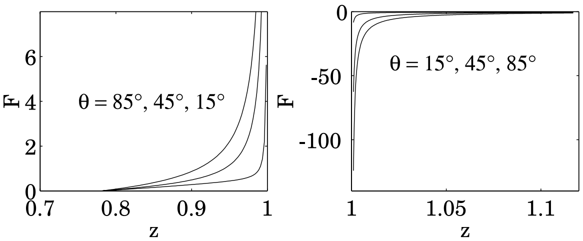

Figure 3. A plot of F versus z (defined in text) for the case of (left) $z < 1$ and (right) $z > 1$. The wave normal angle is given by θ. For $F > 0$ we expect discrete eigenmodes, while for $F < 0$ the eigenvalues are continuous.

and the index of refraction bounding surface at $L = 0$ where L is defined in cold plasma theory by *Stix* [1992]. White lines corresponding to these values are seen in Figure 2b. These lines lie close to the observed emission boundaries, particularly for the $L = 0$ cutoff which is the natural cut off of *Z*-mode emission. The white line depicting f_{UH} falls well below the upper limit of the more continuous emission of the higher-frequency region. We hypothesize that this emission may be *O*-mode from nearby cavities.

[9] *Z*-mode emission is a likely candidate for trapped discrete and continuous emission within the lower-frequency emission region. This emission appears to be trapped within the region defined by the $L = 0$ cutoff as expected for *Z*-mode, and is peaked in intensity when the antenna makes an angle of approximately 90° with respect to the ambient magnetic field. This is also consistent with *Z*-mode or upper hybrid emission.

3. Theory

[10] Magnetoionic dispersion relation for *X*/*Z* mode is given by

$$N^2 = 1 - \frac{f_{pe}^2}{f\,(f + \tau f_{ce})}, \tag{1}$$

where $N = ck/\omega$ is the index of refraction,

$$\tau = \left(s + \sqrt{\cos^2\theta + s^2}\right)\left(f_{pe}^2 - f^2\right)|f_{pe}^2 - f^2|^{-1},$$
$$s = f f_{ce} \sin^2\theta \Big/ \left(2\,|f_{pe}^2 - f^2|\right).$$

For a weakly inhomogeneous medium, we may convert $N^2 \rightarrow -\nabla^2$ and expand the density (assumed to be cylindrically symmetric) by

$$n(r) \approx n(0) + n''(0)\,(r^2/2).$$

This leads to $f_{pe} \rightarrow f_{pe}(0)\,[1 + (n''/2n)\,r^2]$. If we only retain terms linearly dependent on $(n''/n)\,r^2$ on the right-hand side of (1), besides the leading-order terms, then it can be shown that the resulting wave equation is given by

$$\nabla^2\Psi + k_0^2\left(1 - r^2/r_0^2\right)\Psi = 0, \tag{2}$$

where

$$k_0^2 = \frac{4\pi^2 f^2}{c^2}\left(1 - \frac{f_{pe}^2}{f\,(f + \tau f_{ce})}\right),$$
$$r_0^2 = \frac{2n}{n''}\frac{f^2 - f_{pe}^2 + \tau f f_{ce}}{f_{pe}^2}. \tag{3}$$

Without actually solving the above equation, we simply note that in general, the equation of the form,

$$\nabla^2\Phi + \alpha^2\Psi = 0,$$

where $\alpha^2 > 0$ for all r, supports continuous eigenmodes. This can happen if $r_0^2 < 0$, assuming that $k_0^2 > 0$. In order for discrete modes to exist, α^2 must be positive for $r < r_0$, but negative for $r > r_0$. Assuming that $k_0^2 > 0$, such a situation may arise only if $r_0^2 > 0$.

[11] The POLAR observation in Figure 2b shows that a significant transition from discrete to continuous spectrum takes place at $f = f_{pe}$. Thus, if we can establish that

$$r_0^2 > 0 \text{ for } f^2 < f_{pe}^2,$$

while

$$r_0^2 < 0 \text{ for } f^2 > f_{pe}^2,$$

then this would provide a qualitative explanation for the observation. Since $n'' > 0$ for density cavity, we only consider the following quantity:

$$F = z^2 - 1 + \tau\,\epsilon\, z, \tag{4}$$

where

$$\epsilon = f_{ce}/f_{pe},$$

$$z \equiv f/f_{pe}.$$

The quantity τ and s can be expressed as

$$\tau = \left(s + \sqrt{\cos^2\theta + s^2}\right)(1 - z^2)|1 - z^2|^{-1},$$
$$s = \epsilon z \sin^2\theta/(2|1 - z^2|).$$

The condition $F > 0$ is equivalent to $r_0^2 > 0$, and vice versa. Similarly, $z > 1$ is equivalent to $f > f_{pe}$, and vice versa. We consider $\epsilon = 0.5$ as an example, close to the observations of Figure 2. Figure 3 shows that when $z < 1$ (that is, $f < f_{pe}$), then $F > 0$ (implying $r_0^2 > 0$) over a certain frequency range. This shows that discrete eigenmodes can exist over that frequency range. On the other hand, when $z > 1$ (i.e., $f > f_{pe}$), then $F < 0$ (or, equivalently, $r_0^2 < 0$), which means that the eigenvalues are continuous. Thus, the present qualitative eigenvalue analysis gives a plausible first-order explanation for the observations of Figure 2.

4. Summary and Conclusions

[12] We have presented observations of plasma waves that appear to be generated and at least partially trapped in a density cavity located in the nightside plasmapause region.

The data show two distinct regions of emission within the density cavity. The most intense discrete emissions are observed for $f \leq f_{pe}$, while continuous emissions are observed only for $f > f_{pe}$. However, some discrete emissions are observed for $f > f_{pe}$. These may be *O*-mode emission generated from regions of the cavity at higher density or from nearby cavities.

[13] We conclude that the wave fine structure can be explained by eigenvalue analysis (new understanding) and is a diagnostic of small scale density fluctuations perhaps embedded within larger scale structures. The density cavities appear to be 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 [cf. *Yoon and Menietti*, 2005]. Such density structures are thus an important part of the plasmapause/plasmasphere structure and dynamics, and their formation and impact (including the generation of the observed waves) will require much more study.

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