Magnetospheric electron densities inferred from upper-hybrid band emissions

R. F. Benson, 1 P. A. Webb, 2 J. L. Green, 1 L. Garcia, 3 and B. W. Reinisch 4

Received 25 June 2004; revised 13 September 2004; accepted 21 September 2004; published 20 October 2004.

10.1029/2004GL020847


1. Introduction

[1] The magnetospheric electron density $N_e$ can often be obtained to within a few percent from passive radio-wave dynamic spectra when the electron plasma frequency $f_{pe}$ ($\propto N_e^{1/2}$) is greater than the electron cyclotron frequency $f_{ce}$. This conclusion is based on interleaved active and passive observations from the Radio Plasma Imager (RPI) on the IMAGE satellite in the vicinity of the plasmapause. The $N_e$ determinations are based on the frequency limits of an intense narrowband emission identified as the upper-hybrid band. The lower limit is identified with $f_{pe}$ and the upper limit with the upper-hybrid frequency $f_{uh} = (f_{pe}^2 + f_{ce}^2)^{1/2}$. These frequency limits and the large amplitude of the emission, typically 20 dB or more above background, suggest strong Z-mode waves, rather than quasi-thermal fluctuations, as the emission source. INDEX TERMS: 2772 Magnetospheric Physics: Plasma waves and instabilities; 6984 Radio Science: Waves in plasma; 6939 Radio Science: Magnetospheric physics. Citation: Benson, R. F., P. A. Webb, J. L. Green, L. Garcia, and B. W. Reinisch (2004), Magnetospheric electron densities inferred from upper-hybrid band emissions, Geophys. Res. Lett., 31, L20803, doi:10.1029/2004GL020847.

1. Introduction

[1] Enhanced ionospheric and magnetospheric emissions are commonly observed by rocket- and satellite-borne radio receivers in the frequency range between the electron plasma frequency $f_{pe}$ and the upper-hybrid frequency $f_{uh} = (f_{pe}^2 + f_{ce}^2)^{1/2}$, where $f_{ce}$ is the electron cyclotron frequency. They correspond to the slow branch of the extraordinary mode, i.e., the Z mode, and are often referred to as upper-hybrid band emissions. Since the first observations, they have been attributed to non-thermal processes due to their large signal strength (typically 20 dB or more above background). Cherenkov radiation from energetic charged particles is considered the likely source mechanism because of the large refractive index (and hence low wave phase velocities) in this frequency domain [Walsh et al., 1964]. Their importance in determining the magnetospheric electron density $N_e$ (since $(f_{pe} \text{ (kHz)})^2 \approx 80.6 N_e \text{ (cm}^{-3})$) was first convincingly demonstrated by Bauer and Stone [1968]. Determining the magnetospheric $N_e$ from intense upper-hybrid band emissions is still considered to be the most reliable passive technique [Denton et al., 2002]. An uncertainty is introduced, however, if this determination is based strictly on the observed emission-frequency maximum amplitude $f_{mx}$ since it has been observed that while $f_{mx}$ agrees with $f_{pe}$ or $f_{ce}$ to within about 5% for large $f_{pe}/f_{ce}$ ($\approx 4$), it can differ from $f_{pe}$ or $f_{ce}$ by as much as 20% for smaller $f_{pe}/f_{ce}$ ($<3$) [Benson et al., 2002]. In addition, evidence has been presented that inside the plasmasphere, where $f_{pe} \gg f_{ce}$, this emission line corresponds to quasi-thermal fluctuations near $f_{pe}$ [Lund et al., 1994]. The theory and observational evidence for such fluctuations near $f_{pe}$ when $f_{pe} \gg f_{ce}$ has been presented in numerous publications but the treatment in a magnetized plasma is more difficult and in this case the observed emission line has been attributed to quasi-thermal fluctuations near $f_{uh}$ [e.g., see Meyer-Vernet et al., 1998, and references therein]. Here this emission line is investigated for the magnetospheric conditions when $f_{pe}$ is comparable to, and greater than, $f_{ce}$. Specifically, we investigate the relationship of $f_{mx}$, and the lower and upper frequency limits $f_{lo}$ and $f_{up}$, respectively, of the upper-hybrid band emission enhancement to $f_{pe}$ and $f_{uh}$. Data from the Radio Plasma Imager (RPI) [Reinisch et al., 2001] on the Imager for Magnetopause-to-Auroral Global Exploration (IMAGE) satellite [Burch, 2003] are used to compare $f_{pe}$ and $f_{uh}$, determined to within a few percent from active (sounder) measurements, with $f_{lo}$, $f_{mx}$ and $f_{up}$, also determined to within a few percent, from nearly simultaneous passive receiver measurements. The AUREOL/ARCade-3 active (mutual impedance)/passive comparisons of Beghin et al. [1989], between $f_{mx}$ and $f_{pe}$ and $f_{uh}$ and relating $f_{mx}$ and $f_{up}$ to $f_{pe}$ and $f_{uh}$, respectively, claimed similar accuracy but were limited to low altitudes (400–2000 km). (IMAGE is in a highly elliptical polar orbit extending to 8-RE radial distance.) The Cassini active (sounder)/passive comparisons of Kurth et al. [2001] achieved higher altitudes but was limited by a single pass through the magnetosphere, only a brief (5 min) period of active operation and an estimated 5% accuracy Langmuir-probe $f_{pe}$ determination. The goal here is to make numerous active/passive comparisons in the region near and just beyond the plasmapause, so as to cover a range of $f_{pe}/f_{ce}$ values, in order to determine if (1) $f_{lo}$ and $f_{up}$ can be identified with $f_{pe}$ and $f_{uh}$, respectively or (2) $f_{mx}$ can be identified with $f_{uh}$. As per the above discussion, the former conclusion would support a non-thermal Z-mode emission process whereas the latter would support quasi-thermal fluctuations as the source mechanism. A resolution of this question would allow numerous existing passive plasma-wave data sets, and passive plasma-wave data from future missions,
to be analyzed with confidence to make reliable \( N_e \) determinations.

2. Observations

[1] The RPI alternates between active and passive measurements. It employs three mutually orthogonal dipole antennas. Presently, the estimated tip-to-tip lengths of the spin-plane X and Y antennas are 370 m and 470 m, respectively, while the spin-axis Z dipole is 20 m. The RPI active measurements are displayed in the form of plasmagrams. They display the received signals recorded on one of the dipoles, following pulsed transmissions from the X dipole, and are used to determine \( f_{ce} \) (to within \( \pm 0.1\% \)) and \( f_{pe} \) (to within \( \pm 1\% \)) from the stimulated plasma resonances and the Z- & X-mode wave cutoffs [Benson et al., 2003]. The plasmagrams presented here are based on X-dipole reception. The RPI passive measurements are displayed in the form of dynamic spectra (composed of spectral line scans typically separated by 2 minutes). They display signals from space-plasma emission processes and are used to determine (to within \( \pm 1\% \)) \( f_{lo}, f_{up}, \) and \( f_{mx} \) of the upper-hybrid band emission enhancement. The dynamic spectra presented here are based on the combined signals from the X & Y dipoles so as to smooth out antenna spin-modulation effects. This study is based on a comparison of the interleaved passive and active RPI data. The sounder-derived \( f_{pe}, f_{ce} \) and \( f_{up} \) determinations from plasmagrams, such as those shown in Figure 2, were used to estimate the values for these parameters at the appropriate times on the intervening dynamic spectral line scans. Such scan lines, when combined, make up passive dynamic spectra of the type shown in Figure 1. The relative times between the active plasmagrams and the passive dynamic spectral line scans are shown in Figure 3; \( f_{ce}, f_{pe} \) and \( f_{up} \) interpolations onto two consecutive dynamic spectral line scans from one of the cases investigated are shown in Figure 4.

[6] The main uncertainty in this comparison is the linear interpolation of the \( f_{pe} \) values with respect to time during the few minutes of orbital motion separating active soundings. The offset observed in the left panels of Figure 4 between the vertical lines, marking the interpolated \( f_{pe} \) and \( f_{up} \) values, and the open circles and squares marking \( f_{lo} \) and \( f_{up} \) is attributed to this uncertainty. In the next dynamic spectrum, shown in the right panels of Figure 4, there was

Figure 1. IMAGE/RPI passive dynamic spectrum with insert showing the IMAGE orbit in red and orbit-plane projections of the L = 4 and 8 dipole magnetic-field lines in black.

Figure 2. (a) Plasmagram with 0.9 kHz frequency steps from 18 Jan 2001 0237:16 UT (\( f_{pe}/f_{ce} = 62.6/15.6 = 4.0 \) based on plasma resonances at \( f_{pe}, f_{ce}, \) and the X-mode wave cutoff designated by p, u, n and x, respectively). (b) Plasmagram with 1.2 kHz frequency steps from 25 March 2003 0047:09 UT (\( f_{pe}/f_{ce} = 52.5/22.7 = 2.3 \) determined as in (a) above). The Qn and Dn identifications correspond to the calculated positions [see Benson et al., 2003].
Figure 3. Values for $f_{ce}$ (open blue triangles) and $f_{pe}$ (open red circles) from the plasmagrams, and the times (vertical black line segments) of the intervening dynamic spectral line scans, for the four time intervals investigated. Straight lines connect the $f_{ce}$ and $f_{pe}$ values.

exact agreement between the interpolated $f_{pe}$ and $f_{uh}$ values and the steep edges of the signal enhancement. In addition to comparing individual cases as in Figure 4, a combined comparison was made to the dynamic spectra of Figure 3 with $f_{pe}/f_{ce} > 1$. This combined comparison tends to average out the interpolation uncertainties. The results, where all frequencies are normalized by $f_{ce}$, are presented in Figure 5.

The statistical results of Figures 5a and 5b indicate that while the gradients for the comparisons between $f_{mx}$ and $f_{pe}$ and $f_{uh}$ are equal to or near unity, the intercepts do not equal zero. Unity gradients and zero intercepts are achieved, however, in the results presented in Figures 5c and 5d where $f_{lo}$ and $f_{up}$ are compared to $f_{pe}$ and $f_{uh}$, respectively. Thus these statistical results support the impression given in the lower right panel of Figure 4, i.e., that $f_{pe}$ corresponds to $f_{lo}$ and $f_{uh}$ corresponds to $f_{up}$. The Figure 5 results are dependent on the $f_{lo}$ and $f_{up}$ edge definitions. Too small a signal drop from the $f_{mx}$ value leads to results more subject to the background noise level since the $f_{mx}$ level is often only a few dB above the general upper-hybrid band enhancement of about 20 dB or more (see the bottom panels of Figure 4). Too large a signal drop leads to results more subject to the influence of adjacent resonances and the background noise level. The 14 dB value used in Figures 4 and 5 was selected because it gave gradient and intercept values of 1.00 and 0.00 (within the linear-regression uncertainties), respectively, in Figures 5c and 5d while maintaining high linear-regression coefficients ($\geq 0.984$ for signal drop $\leq 14$ dB). Approximately half of the errors indicated in Figure 5 are due to the one value near $f_{pe}/f_{ce} = 3$ and $f_{uh}/f_{ce} = 3$, well below the straight-line fit, in the left and right panels of Figure 5, respectively (the corresponding intercept values would change slightly by removing this point, i.e., they would become 0.22, $-0.19$, 0.01 and $-0.01$ in panels a, b, c and d, respectively). It corresponds to the 1926 UT dynamic spectral line scan in the lower left panel of Figure 3. Here the true negative $f_{pe}$ gradient, just beyond 1925 UT, was apparently much steeper than indicated by the linear interpolation.

In addition to the active/passive comparisons shown in Figures 4 and 5, a comparison was made that did not introduce interpolation assumptions. It is presented in Figure 6. Here plasmagram-determined $f_{ce}$, $f_{pe}$ and $f_{uh}$ values from active sounding were superimposed on the passive RPI dynamic spectrum corresponding to the same time interval. The upper-hybrid band is relatively broad

Figure 4. Two consecutive passive dynamic spectral line scans with superimposed interpolated frequencies from active plasmagrams. The lower panel enlargements clearly show the relationship between the interpolated $f_{pe}$ and $f_{uh}$ values (red and green vertical lines, respectively) and the observed $f_{lo}$ (open red circles), $f_{mx}$ (open black diamonds) and $f_{up}$ (open green squares). ($f_{pe}/f_{ce}$ (interpolated) = 56.2/41.4 = 1.4 and 50.2/39.7 = 1.3 in the left and right panels, respectively.)

Figure 5. Combined normalized comparisons of the 35 $f_{pe}/f_{ce} > 1$ dynamic spectra of Figure 3. (a and b) $f_{mx}$ compared to the interpolated $f_{pe}$ and $f_{uh}$, (c) $f_{lo}$ compared to the interpolated $f_{pe}$, and (d) $f_{up}$ compared to the interpolated $f_{uh}$. The gradient and ordinate-axis intercept in each case were based on fitting only the $f_{pe}/f_{ce} > 1$ data to a straight line. The blue open triangles, corresponding to $f_{pe}/f_{ce} < 1$, were not used in this fitting.
(extending from ≈50 to 60 kHz) near 00:30 UT where $f_{pe} \approx f_{ce}$ and it narrows in bandwidth as time progresses. The scaled $f_{pe}$ and $f_{uh}$ frequencies in the region beyond about 00:30 UT, i.e., in the region where $f_{pe} > f_{ce}$, allow the boundaries of the upper-hybrid band to be identified and distinguished from the slanting finger-like higher-frequency emissions. These emissions are attributed to $Q_n$ emissions, which are often observed between the $n f_{ce}$ harmonics at frequencies greater than $f_{uh}$ [see, e.g., Benson et al., 2003], and they can hinder an accurate determination of $f_{up}$. When $f_{pe} < f_{ce}$ the determination of $f_{up}$ can be compromised by the lack of a well defined emission peak.

3. Discussion and Conclusions

[10] The IMAGE/RPI active/passive comparisons presented here indicate that the upper-frequency edge $f_{up}$ of the upper-hybrid band enhancement (of typically 20 dB) on passive RPI magnetospheric dynamic spectra is equal to $f_{uh}$, and the lower-frequency edge $f_{lo}$ is equal to $f_{pc}$, when $f_{pe} > f_{ce}$ to an accuracy of a few per cent in $f_{pe}$. These results, which emphasize the importance of the frequency extremes of the large emission enhancement rather than the frequency of the maximum, support the non-thermal Z mode rather than the quasi-thermal mechanism. They were confirmed from fmx required to achieve 14-dB signal reductions. These spreads are caused by the great frequency separations from $f_{mx}$ required to achieve 14-dB signal reductions. Beghin et al. [1989] never observed an enhancement when $f_{pe} < f_{ce}$; they attribute this finding to a lack of instability growth of Z-mode waves in the upper-hybrid band under these conditions. This frequency domain, as well as the domain of $f_{pe} \approx f_{ce}$ requires more investigation.

[11] Plasmagrams such as the ones shown in Figure 2 provide multiple determinations of $f_{pe}$. Passive magnetospheric dynamic spectra can also often offer more than one determination of $f_{pe}$ in the frequency domain $f_{pe} > f_{ce}$ (a common magnetospheric condition). Since $N_e$ is proportional to $f_{pe}$, it can be determined either directly from $f_{pe}$ or from $f_{uh}$ with knowledge of $f_{ce}$ from either a magnetic-field model or a scientific magnetometer. Thus two $N_e$ determinations will result from the detection of the lower and upper frequency limits of the upper-hybrid band. When $f_{pe}$ increases to beyond about $4 f_{ce}$, where $f_{uh}$ exceeds $f_{pe}$ by <3%, the $f_{up} - f_{lo}$ separation becomes comparable to the instrument frequency resolution so that only a single estimate of $f_{pe}$ is possible, namely, by considering $f_{up} (\approx f_{mx}) = f_{uh} (\approx f_{pe})$.

[12] Acknowledgments. This work received support from NSF ATM-0245664, and from subcontract 83822 from Southwest Research Institute to UML under NASA contract NAS5-96020. We are grateful to D. L. Carpenter for helpful comments.

References


