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Electromagnetic Components of Auroral Hiss and Lower Hybrid Waves in the Polar Magnetosphere

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DE-1 has frequently observed waves in the whistler and lower hybrid frequencies range. Besides the electrostatic components, these waves also exhibit electromagnetic components. It is generally believed that these waves are excited by the electron acoustic instability and the electron-beam-driven lower hybrid instability. Because the electron acoustic and the lower hybrid waves are predominately electrostatic waves, they can not account for the observed electromagnetic components. In this work, it is suggested that these electromagnetic components can be explained by waves that are generated near the resonance cone and that propagate away from the source. The role that these electromagnetic waves can play in particle acceleration processes at low altitude is discussed.

INTRODUCTION

The Earth's polar magnetosphere has long been recognized as an active region of wave activities. In the last two decades, numerous spacecraft have sampled this region of space and have identified a large variety of wave modes, most notably, the auroral hiss and the auroral kilometric radiation (for a review, see Shawhan, 1979). These waves are believed to play an important role in various plasma processes in the magnetosphere through wave-particle interactions. Examples of such processes include the diffusion of auroral electrons by electrostatic electron cyclotron waves (Ashour-Abdalla and Kennel, 1978); the generation of the auroral kilometric radiation through relativistic cyclotron resonance (Gurnett, 1974; Wu and Lee, 1979); and the acceleration and heating of ions and electrons by waves in the auroral region, leading to the formation of ion and electron conical distributions (Chang et al., 1986; Lysak, 1986; Wong et al., 1988; Crew et al., 1990; Temerin and Cravens, 1990).

One of the wave modes that has been extensively studied in the past is the whistler mode. This is mainly due to the interest in VLF emissions, auroral hiss, and lighting-related phenomena. In the mid-altitude polar magnetosphere, the electron plasma frequency ω_{pe} is typically less than the electron cyclotron frequency Ω_e. Under this condition, the whistler mode propagates between the lower hybrid frequency, which is approximately the ion plasma frequency ω_{pi}, and the electron plasma frequency. The frequently observed whistler mode auroral hiss is believed to be generated near the resonance cone by either precipitating electrons or upward moving electron beams (Gurnett et al., 1983). Another wave mode that has received considerable attention is the lower hybrid wave. The lower hybrid wave has also been observed in the auroral zone and the polar cusp and can be generated near the resonance cone by either an electron beam or an ion ring distribution (Maggs, 1976; Roth and Hudson, 1985). One distinct feature of the lower hybrid wave is that it can accelerate both electrons and ions and might be the source for auroral precipitating electrons and ion conics (Bingham et al., 1984; Chang and Coppi, 1981).

The whistler and lower hybrid waves excited near the resonance cone are quasi-electrostatic waves with negligible magnetic components. However, the "funnel-shaped" auroral hiss observed by DE-1 signifies that the auroral hiss has considerable magnetic components (Gurnett et al., 1983). Subsequent stability analyses using the observed particle distributions have revealed that the electron acoustic wave,

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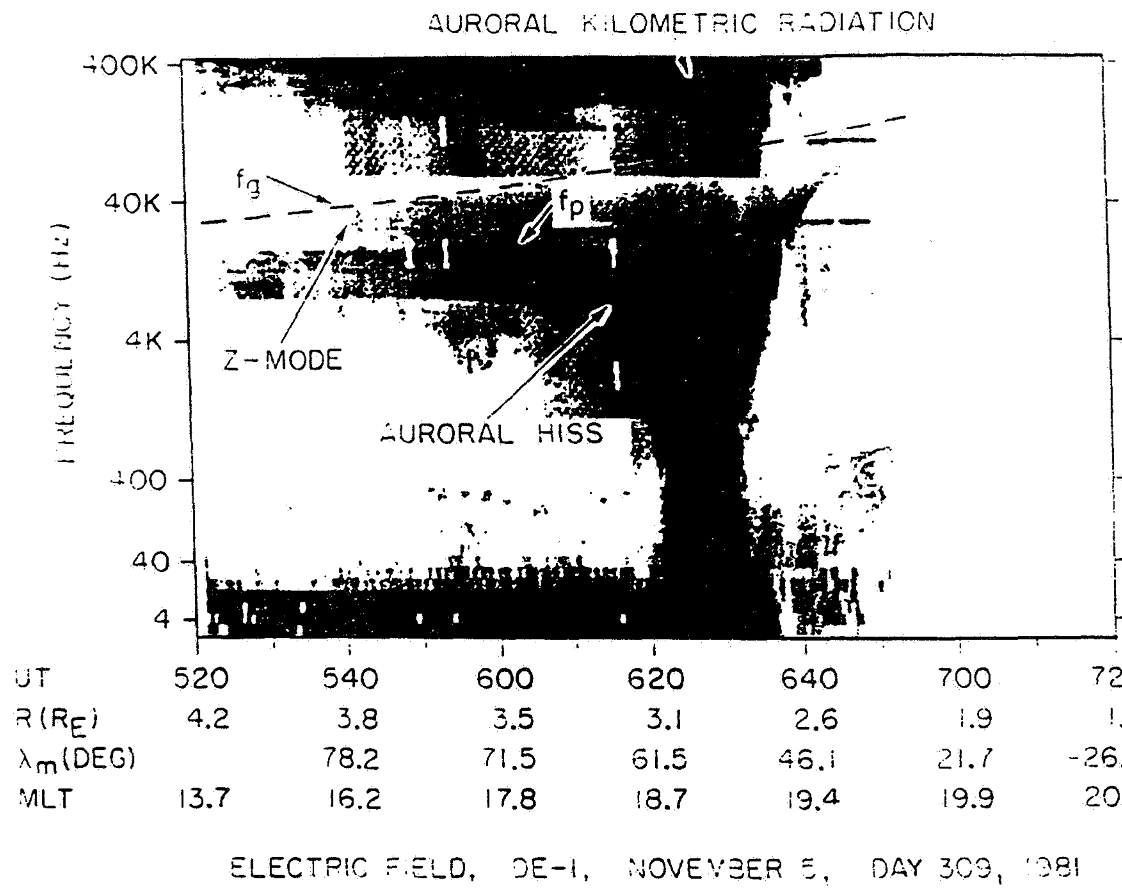

Fig. 1. A representative spectrogram of the electric field intensities for a nightside crossing of the auroral field lines. The plasma density over the polar region is relatively low, with $f_p << f_g$ (from Gurnett et al., 1983).

rather than the whistler wave, is the more unstable mode driven by the electron beam (Lin et al., 1984, 1985; Tokar and Gary, 1984). The electron acoustic wave is electrostatic in nature and thus might account for the electrostatic component of auroral hiss. The origin of the electromagnetic component of the hiss, however, still remains unanswered. In a different context, Benson et al. (1988) have reported the ground-based detection of waves in the frequency range of 150-300 kHz, which indicates the generation of field-aligned waves in the auroral zone. The field-aligned waves observed by Benson et al. are electromagnetic and fall into the frequency range of the whistler mode. Motivated by these observations, Wu et al. (1989) showed that an energetic electron population with a temperature anisotropy or a trapped type distribution is capable of generating field-aligned waves in the observed frequency range.

In this paper, we present data obtained from the Plasma Wave Instrument (PWI) and the High Altitude Plasma Instrument (HAPI) onboard the DE-1 spacecraft. We are mainly interested in electromagnetic waves with frequencies between the ion cyclotron and the electron cyclotron frequencies and the correlation of these waves with the plasmas. As shown below, we have identified broadband, low-frequency electromagnetic waves in the vicinity of the lower hybrid frequency. We have also found examples of electromagnetic waves in the whistler frequency range, which is quite different from the funnel-shaped auroral hiss. We believe that these electromagnetic waves are first generated either by electron beams or ion rings as the lower hybrid or whistler mode near the resonance cone and acquire electromagnetic components when they propagate away from the sources.

OBSERVATIONS

Figure 1 shows a frequency-time spectrogram (from Fig. 4 of Gurnett et al., 1983) during a nightside crossing of the auroral field lines under the condition that the electron plasma frequency, ω_{pe}, is less than the electron cyclotron frequency, Ω_e. The corresponding electric field intensity spectrum is shown in Figure 2 (from Fig. 5 of Gurnett et al., 1983). These figures display some common features of high-frequency electromagnetic waves frequently observed in the low-density auroral region. At or above the electron cyclotron frequency is the auroral kilometric radiation, which is believed to be in the fast extraordinary (R-X) mode. The Z mode radiation is observed at or below the local electron cyclotron frequency, with some possible overlap of ordinary (L-O) mode radiation (the upper cutoff of the Z mode is at the upper hybrid frequency, which is very close to the electron cyclotron frequency for a low-density plasma). The auroral hiss is the most commonly observed and is bounded by the electron plasma frequency (for $\omega_{pe} < \Omega_e$). Auroral hiss falls into the whistler mode range and exhibits a funnel-shape centered on a region of intense electron precipitation (Gurnett et al., 1983).

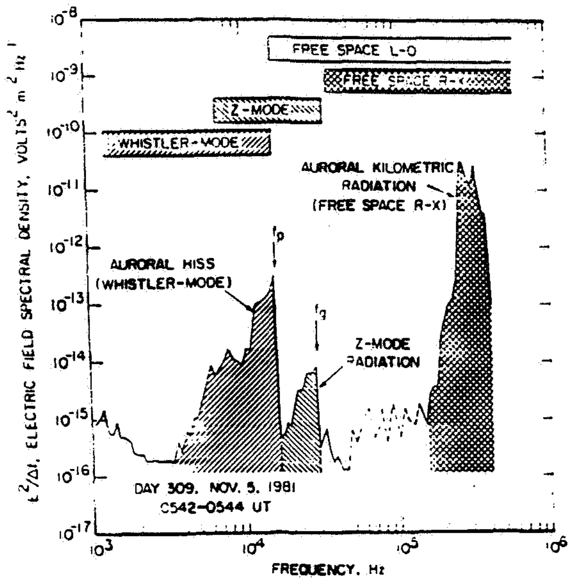

Fig. 2. An electric field intensity spectrum selected from the pass in Figure 1 showing the relative intensities of the auroral kilometric radiation, the Z mode radiation, and the auroral hiss. The sharp upper cutoff of the auroral hiss at f_p and the cutoff of the Z mode radiation at f_g are clearly evident. The dashed line indicates a region where the spectrum is being modified by receiver distortion effects caused by the very intense kilometric radiation (from Gurnett et al., 1983).

Besides the high-frequency electromagnetic waves, low-frequency electromagnetic waves with frequencies at or below the ion cyclotron frequencies have also been observed in the polar region [see Gurnett et al. (1984) for a detailed discussion]. However, not much attention has been paid to electromagnetic waves between the ion cyclotron and the lower hybrid frequencies. One of the main purposes of the present work is to show that electromagnetic waves in this frequency range are a common occurrence in the polar magnetosphere and to explore the roles that these waves can play in particle acceleration processes at low altitude. As a first example, Plate 1 (adapted from Sharber et al., 1988) shows the particle and wave observations in the dayside auroral zone. The upper panel shows the electron data. The middle and lower panels display the electric and magnetic spectra. It is clear from the electric and magnetic field signatures that the most intense electromagnetic waves occurred between 06:50 UT and 07:15 UT. These electromagnetic waves have frequencies between 200 Hz and 700 Hz, whereas the local electron cyclotron frequency (represented by the dotted line) is approximately 25 kHz and the corresponding hydrogen cyclotron frequency is approximately 13.5 Hz. Thus, these electromagnetic waves are above the ion cyclotron frequency and are in the vicinity of the lower hybrid frequency. Two features of these waves are worth mentioning. First, these waves occurred outside the region of intense electron precipitation (~ from 07:45 UT to 08:00 UT) in which broadband electrostatic waves are observed. Second, the electromagnetic waves are observed at the higher magnetic field side of the electron precipitation. These features provide some clue of how these waves are generated, which we will discuss later.

Plate 2 shows an example of particle and wave observations in the nightside auroral zone. The upper panel shows the electron data while the middle and lower panels display the electric and magnetic field data. The electric field data showed a rather weak auroral kilometric radiation, which lies above the electron cyclotron frequency (the upper dotted line), suggesting that the AKR is generated below the satellite. The funnel-shaped auroral hiss emission shows a strong correlation with the auroral precipitating electrons, which is centered at approximately 07:33 UT. There are two distinct bands of emissions just outside the precipitating region, started from 07:43 UT. The first band of emission has a frequency range from 200 Hz to 500 Hz. This band of emission is essentially the same type of emission that we just discussed, with frequencies extending from above the ion cyclotron frequency (the lower dotted line) to the lower hybrid frequency. The second band of emission has a frequency range from 500 Hz to 2 kHz. This band of emission has a frequency above the lower hybrid frequency and falls into the whistler mode range. An examination of the magnetic field data suggested that these two bands of emissions are electromagnetic. These two bands of electromagnetic emissions also have the same features as the case that we discussed above, i.e., they are observed outside the region and at the higher magnetic field side of intense electron precipitation.

In addition to the two examples shown above, our preliminary survey of the DE plasma wave data has found numerous examples of these electromagnetic waves in the auroral zone, polar cusp, and polar cap. The lower band of these electromagnetic waves typically has frequencies between 100 Hz and 1 kHz, falling between the ion cyclotron and lower hybrid frequencies. The upper band emissions have frequencies above the lower hybrid frequency and are in the whistler mode range. However, their characteristics are very different from the auroral hiss whistler mode. In the following, we try to identify these waves and explore the possibilities of how these waves are generated.

DISCUSSION AND SUMMARY

Our initial interpretation of the electromagnetic waves with frequencies between the ion cyclotron and the lower hybrid frequencies are fast magnetosonic waves since fast magnetosonic waves are the only electromagnetic waves in this frequency range that exhibit such characteristics (to our best knowledge). The other band of electromagnetic emissions with frequencies above the lower hybrid frequency (but far below the electron cyclotron frequency) are probably electromagnetic whistler waves. One immediate question to ask is whether these waves are locally generated and by what mechanisms. It seems highly unlikely that these waves are locally generated based on the following considerations. First, the fast magnetosonic wave has a phase speed at or above the Alfvén speed, which is very high for a low density plasma (at least of the order of 0.1 c, with c being the speed of light). Thus Landau resonance can not easily be satisfied between the waves and the particles, except for very energetic electrons (10's of keV or higher). However, electrons with energies 10 keV or higher are seldom observed in the dayside polar region. Second, when wave frequencies are far above the ion cyclotron frequency but far below the electron cyclotron frequency, it is very difficult for cyclotron resonance to occur. This might be the main reason that little attention has been paid to electromagnetic waves in this frequency range since there is no obvious direct means of generating electromagnetic waves in this regime. Third, when these electromagnetic waves are observed, there is little activity among the plasmas.

If one rules out the possibility that these waves are locally generated, one can easily provide an explanation for the occurrence of these waves. We suspect that these waves are generated first as lower hybrid waves near the lower hybrid resonance cone above the satellite in field lines under which the particle precipitation occurs and propagates downward. Lower hybrid waves can be excited either by electron beams in the auroral zone or by ion ring distribution in the polar cusp. As the lower hybrid waves propagate toward higher magnetic field strength, the waves become more electromagnetic and eventually transit into fast magnetosonic waves. As the waves propagate toward lower magnetic field strength, the waves become more electrostatic and are absorbed by the background plasmas. The same mechanism can also apply to the electromagnetic whistler waves except whistler waves can only be generated by electron beams since the frequency of the waves is too high for ions to respond. This scenario explains naturally why these waves are mainly observed outside the region and at the higher magnetic field side of intense electron precipitation.

We now divert our attention to what role the fast magnetosonic waves can play in particle acceleration processes at low altitude. The acceleration of ionospheric ions and the formation of ion conics have been extensively studied in the past. Despite the fact that electrostatic ion cyclotron and lower hybrid heating are regarded as the promising ion acceleration mechanisms and these waves have frequently been observed in the polar regions, there is no conclusive evidence that these waves are correlated with ion conics (Kitner and Gorney, 1984). Also, there is considerable doubt whether these processes are operative at low altitudes, probably as low as 400 km, where ion conics have been observed (Yau et al., 1983). The electrostatic ion cyclotron waves are difficult to excite at low altitudes since it requires a very large critical current. The lower hybrid wave has too high a phase velocity to resonate with the cold ionospheric ions. One way to get around this difficulty is to assume that the lower hybrid waves undergo a parametric decay process. The resulting daughter lower hybrid waves have lower phase velocity and can resonate with the thermal ions (Koskinen, 1985; Retterer et al., 1986). However, this process requires intense lower hybrid pump waves, but there is no strong observational support of intense lower hybrid waves at very low altitudes. As was just mentioned, fast magnetosonic waves have a very high phase velocity when the wave frequency is not too close to lower hybrid frequency. Thus, the wave can propagate a long distance downward practically undamped, until the wave frequency is very close to the local ion cyclotron frequency in which ion cyclotron damping occurs. (The fast magnetosonic wave consists of both right and left hand components. The left hand component contributes to cyclotron damping). This process leads to the heating or acceleration of ions at low altitudes by fast magnetosonic waves originating at high altitudes and also provides additional support that the fast

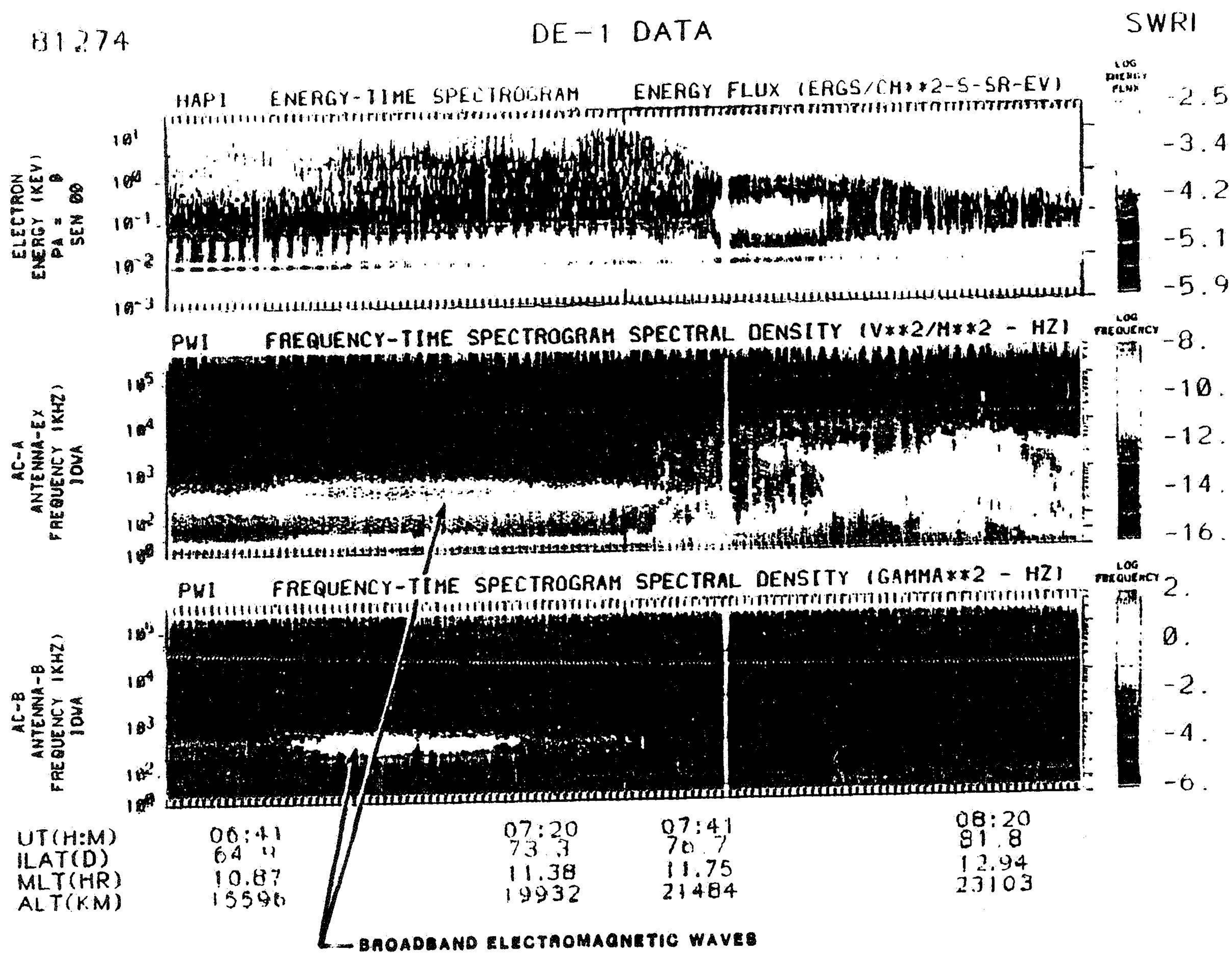

Plate 1. Dayside example of simultaneous particle and wave measurements from DE-1. The upper panel shows the electron data. The middle and lower panels display the electric and magnetic spectra (adapted from Sharber et al., 1988).

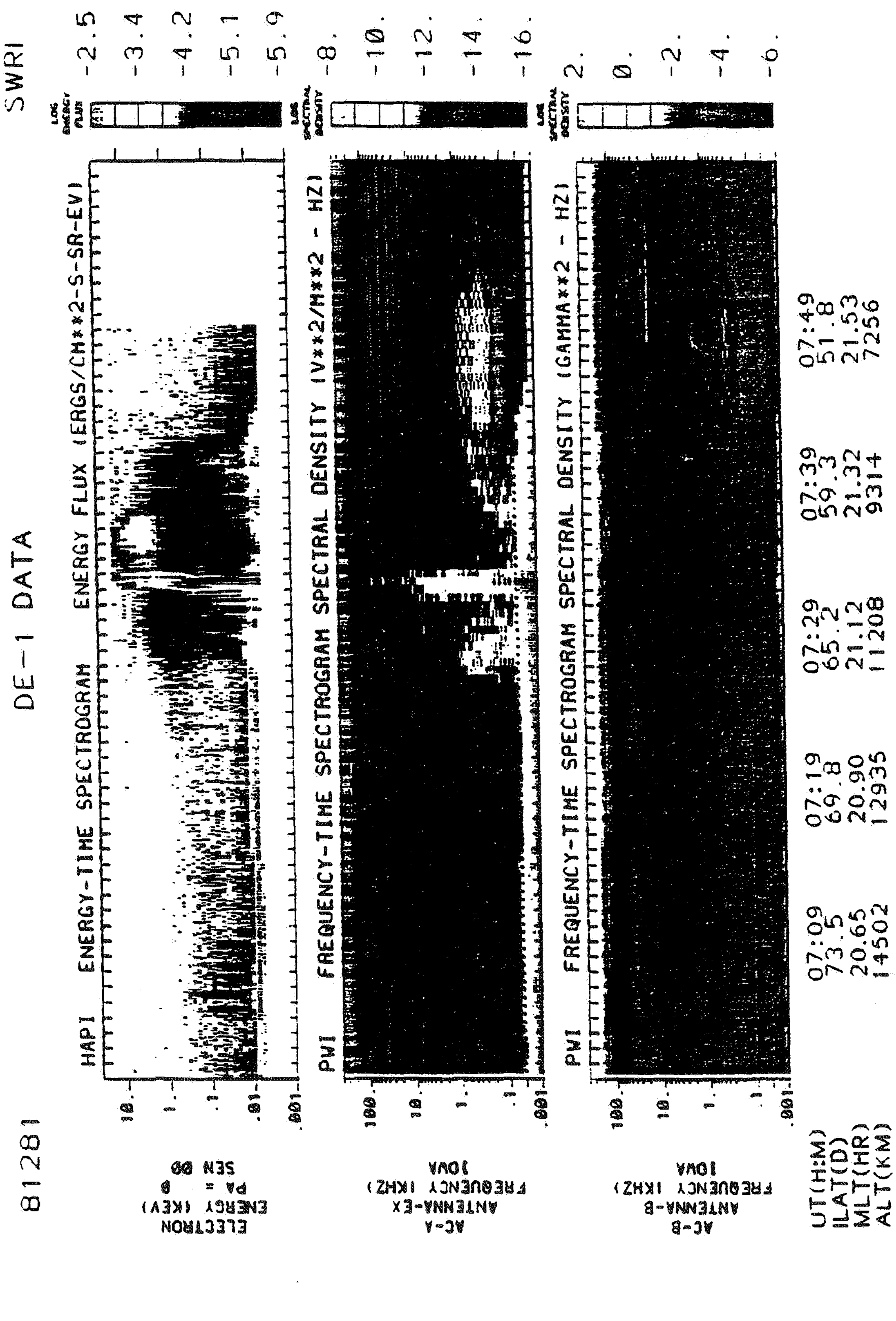

Plate 2. Nightside example of particle and wave measurements. The two distinct bands of electromagnetic emissions centered at approximately 07:50 UT.

magnetosonic waves are often observed at above, not below, the ion cyclotron frequency.

In summary, it has been shown through examples from DE-1 wave and plasma data that electromagnetic waves with frequencies between the ion cyclotron and the electron cyclotron frequencies are common occurrences in the Earth's polar magnetosphere. It is suggested that these electromagnetic waves are first generated either by electron beams or ion rings as the lower hybrid or whistler mode nears the resonance cone and then they acquire electromagnetic components when propagated away from the sources toward higher magnetic field strengths. The fast magnetosonic waves might play an important role in the acceleration of ions at low altitudes as they propagate toward the ionosphere. Further studies which include stability analysis using the observed particle distributions, ray tracing, and quasilinear and nonlinear analysis are desirable to examine quantitatively the origin of these waves, how they propagate down to the ionosphere, and their subsequent heating of cold ionosphere ions through cyclotron damping.

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REFERENCES

Ashour-Abdalla, M., and C. F. Kennel, Diffuse auroral precipitation, *J. Geomag. Geoelectr.*, *30*, 239, 1978.

Benson, R. F., M. D. Desch, R. D. Hunsucker, and J. G. Romick, Ground-level detection of low and medium-frequency auroral emissions, *J. Geophys. Res.*, *93*, 277, 1988.

Bingham, R., D. A. Bryant, and D. S. Hall, A wave model for the aurora, *Geophys. Res. Lett.*, *11*, 327, 1984.

Chang, T., and B. Coppi, Lower hybrid acceleration and ion evolution in the suprauroral regions, *Geophys. Res. Lett.*, *8*, 1253, 1981.

Chang, T., G. B. Crew, N. Hershkowitz, J. R. Jasperse, J. M. Retterer, and J. D. Winningham, Transverse acceleration of oxygen ions by electromagnetic ion cyclotron resonance with broadband left-hand polarized waves, *Geophys. Res. Lett.*, *13*, 636, 1986.

Crew, G. B., T. Chang, J. M. Retterer, W. K. Peterson, D. A. Gurnett, and R. L. Huff, Ion cyclotron resonance heated conics: Theory and observations, *J. Geophys. Res.*, *95*, 3959, 1990.

Gurnett, D. A., The Earth as a radio source: Terrestrial kilometric radiation, *J. Geophys. Res.*, *79*, 4227, 1974.

Gurnett, D. A., S. D. Shawhan, and R. R. Shaw, Auroral hiss, Z mode radiation, and auroral kilometric radiation in the polar magnetosphere: DE-1 observations, *J. Geophys. Res.*, *88*, 329, 1983.

Gurnett, D. A., R. L. Huff, J. D. Menietti, J. L. Burch, J. D. Winningham, and S. D. Shawhan, Correlated low-frequency electric and magnetic noise along the auroral field lines, *J. Geophys. Res.*, *89*, 8971, 1984.

Kitner, P. M., and D. J. Gorney, A search for the plasma processes associated with perpendicular ion heating, *J. Geophys. Res.*, *89*, 937, 1984.

Koskinen, H. E. J., Lower hybrid parametric processes on auroral field lines in the topside ionosphere, *J. Geophys. Res.*, *90*, 8361, 1985.

Lin., C. S., J. L. Burch, S. D. Shawhan, and D. A. Gurnett, Correlation of auroral hiss and upward electron beams near the polar cusp, *J. Geophys. Res.*, *89*, 925, 1984.

Lin, C. S., D. Winske, and R. L. Tokar, Simulation of the electron acoustic instability in the polar cusp, *J. Geophys. Res.*, *90*, 8269, 1985.

Lysak, R. L., Ion acceleration by wave-particle interaction, in *Ion Acceleration in the Magnetosphere and Ionosphere*, edited by T. Chang, p. 261, A. G. U., Washington, D. C., 1986.

Maggs, J. E., Coherent generation of VLF hiss, *J. Geophys. Res.*, *81*, 1707, 1976.

Retterer, J. M., T. Chang, and J. R. Jasperse, Ion acceleration by lower hybrid waves in the suprauroral region, *J. Geophys. Res.*, *91*, 1609, 1986.

Roth, I., and M. K. Hudson, Lower hybrid heating of ionospheric ions due to ion ring distribution in the cusp, *J. Geophys. Res.*, *90*, 4191, 1985.

Sharber, J. R., J. D. Menietti, H. K. Wong, J. L. Burch, D. A. Gurnett, J. D. Winningham, and P. J. Tanskanen, Plasma waves associated with diffuse auroral electrons at mid-altitudes, *Ad. Space Res.*, *8*, no. 9, 447, 1988.

Shawhan, S. D., Magnetospheric plasma waves, in *Solar System Plasma Physics*, vol. III, edited by L. J. Lanzerotti, C. F. Kennel, and E. N. Parker, North-Holland, Amsterdam, 1979.

Temerin, M. A., and D. Cravens, Production of electron conics by stochastic acceleration parallel to the magnetic field, *J. Geophys. Res.*, *95*, 4285, 1990.

Tokar, R. L., and S. P. Gary, Electrostatic hiss and the beam driven electron acoustic instability in the dayside polar cusp, *Geophys. Res. Lett.*, *11*, 1180, 1984.

Wong, H. K., J. D. Menietti, C. S. Lin, and J. L. Burch, Generation of electron conical distributions by upper hybrid waves in the Earth's polar region, *J. Geophys. Res.*, *93*, 10025, 1988.

Wu, C. S., and L. C. Lee, A theory of the terrestrial kilometric radiation, *Astrophys. J.*, *230*, 621, 1979.

Wu, C. S., P. H. Yoon, and H. P. Freund, A theory of electron cyclotron waves generated along auroral field lines observed by ground facilities, *Geophys. Res. Lett.*, *16*, 1461, 1989.

Yau, A. W., B. A. Whalen, A. G. McNamara, P. J. Kellogg, and W. Bernstein, Particle and wave observations of low altitude ionospheric ion acceleration events, *J. Geophys. Res.*, *88*, 341, 1983.

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Reply

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Orlowski and Russell [this issue] claim that the energetic electron distributions used by *Wong and Smith* [1994] in a general theoretical study of instabilities at whistler mode frequencies is irrelevant to the wave observations studied by Orlowski and colleagues. We never claimed to model specific electron distributions or to account for particular magnetic wave observations. We begin this reply by clarifying the *Orlowski and Russell* [this issue] description of our work, and we end it by showing that ample justification can be found in the work of Orlowski and colleagues and elsewhere to justify the pursuit of a better theoretical understanding of these instability mechanisms.

Wong and Smith [1994] focuses primarily on the excitation at 1 AU of parallel-propagating waves at whistler mode frequencies with plasma-frame frequencies in the range 10 to 20 Hz. The spacecraft-frame frequencies tend to be similarly valued, so our paper addresses primarily waves that are observable in the lowest channels of plasma wave experiments. *Orlowski and Russell* [1991] and *Orlowski et al.* [1990, 1993, 1995] investigate waves at spacecraft-frame frequencies of ~ 1 Hz observed by magnetometers upstream of Mercury, Venus, and Earth.

The principal motivation for our paper is our own work with whistler mode waves upstream of the Uranian bow shock [*Smith et al.*, 1991]. In that study we report two instances of simultaneous whistler mode waves existing at two different spacecraft frequencies, with different propagation directions and different amplitudes. We conclude that the likely source of the observations is a hot electron beam with $T_{\perp b} > T_{\parallel b}$ originating at or behind the shock. *Wong and Smith* [1994] carries this analysis to 1 AU and searches for the implications this work might have for whistler mode waves in the terrestrial foreshock.

Energetic electron observations recorded close to the shock [*Feldman et al.*, 1983; *Fitzenreiter et al.*, 1984, 1990; *Scudder et al.*, 1986] justify our range of particle distribution parameters. For instance, Figure 1 of *Fitzenreiter et al.* [1990] clearly shows several examples of hot electron beams with $T_{\perp b} > T_{\parallel b}$ and $v_b = (4-8) \times 10^8$ cm/s.

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We take as our base parameterization: $n_p = n_e = 6$ cm^{-3}, $T_p = T_e = 10$ eV, $B = 5$ nT, $n_b = 0.6$ cm^{-3}, $T_b = 100$ eV, $T_{\parallel b} = T_{\perp b}$, $v_b = 3.4 \times 10^8$ cm/s. The resulting instability is maximum at parallel propagation with $k = 1.6 \times 10^{-6}$ and $\omega = 130$ rad/s (21 Hz). This yields spacecraft-frame frequencies greater than 11 Hz (if the solar wind speed is 400 km/s and the wave propagates sunward along a radial magnetic field) and frequencies as high as 21 Hz if the wave propagates at right angles to the solar wind velocity. These frequencies are well above the range of any magnetometers used by Orlowski and collaborators.

From this starting point, we vary the above parameters and make use of an anisotropic electron beam. This destabilizes the obliquely propagating waves through the same mechanism as *Sentman et al.* [1983] and shows that the generation of two simultaneous whistler mode waves at distinct frequencies and propagation directions is again possible at 1 AU as it is at 20 AU. We also demonstrate that the beam-plasma system possesses an unstable mode that is left-hand polarized at whistler mode frequencies. We examine the full range of oblique propagation using numerical codes and develop a simple analytical treatment of the parallel-propagating instabilities.

It is possible to produce parallel-propagating waves with Doppler-shifted spacecraft-frame frequencies as low as 1 Hz if the beam speed is small. We show one such solution in Figure 4 of our paper. However, it is more likely that 1-Hz waves are obliquely propagating when generated by this mechanism and Figures 1, 3, 4, and 6 of our paper demonstrate this fact. All of the oblique solutions with large growth rates shown in these figures have spacecraft-frame frequencies of the order of 1 Hz. While *Orlowski et al.* [1995] contend that a seven-temperature distribution of energetic electrons is essential to the interpretation of the oblique whistler mode instability, it is at best desirable for the interpretation of specific events. Our paper is a more general theoretical treatment of the basic instability.

Wong and Smith [1994] does not attempt to link the theoretical treatment discussed above to any specific magnetic wave observations. It is strictly a theoretical discussion of instabilities leading to electromagnetic waves at whistler mode frequencies that may be present in the Earth's foreshock. However, we note that *Orlowski and Russell* [1991] and *Orlowski et al.* [1990, 1995] claim that 1-Hz magnetic waves originate near the shock and propagate into the upstream region. They also acknowledge that the electron distributions observed concurrent with 1-Hz waves in the upstream region may result from the interaction of the beam with preexisting waves and may not represent the source of the 1-Hz fluctuations. The instabilities we discuss could be operating closer to the shock and may be a source of the 1-Hz waves seen further upstream.

Orlowski et al. [1990] report that the majority of 1-Hz waves upstream of Mercury and Venus are left-hand polarized. Since only *Newman et al.* [1988] and *Wong and Smith* [1994] demonstrate the ability to produce left-hand polarized waves at whistler mode frequencies, the possibility that this mechanism may explain the left-handed waves is worthy of further examination. The relevance of this instability should not be minimized. *Orlowski et al.* [1990, p. 2295] write about 1-Hz waves upstream of Venus:

> The only waves with sufficient group velocity to stand in the flow are whistler mode waves. ...the observed waves must be in fact right-handed in the plasma frame... This explains the apparent paradox of a left-handed wave having a compressional component.

The electron population responsible for the whistler waves upstream of Saturn [*Orlowski et al.*, 1992] is not resolved by observations. The implication by Orlowski and Russell that further discussion of possible source mechanisms for these waves is irrelevant seems premature.

In summary, *Wong and Smith* [1994] is a theoretical discussion of electron beam instabilities at 1 AU that emphasized anisotropic temperature distributions in the generation of right- and left-hand polarized electromagnetic waves at whistler mode frequencies. That paper lays the groundwork for an improved theoretical description of these instabilities and provides an analytical treatment of the instabilities. Waves at whistler mode frequencies upstream of planetary bow shocks possess a wide variety of possible sources. We have no quarrel with arguments by Orlowski and coauthors that whistler mode waves in planetary foreshocks may originate close to the shock and may not be excited by the more distant upstream energetic electron distributions observed concurrent with the waves. In fact, we contend that the broad class of energetic electron observations observed close to the shock may provide the source for at least a class of upstream whistler waves. We believe that pursuit of these instabilities over a wide range of parameter space is worthwhile.

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References

Feldman, W. C., R. C. Anderson, S. J. Bame, S. P. Gary, J. T. Gosling, D. J. McComas, M. F. Thomson, G. Paschmann, and M. M. Hoppe, Electron velocity distributions near the Earth's bow shock, *J. Geophys. Res.*, *88*, 96-110, 1983.

Fitzenreiter, R. J., A. J. Klimas, and J. D. Scudder, Detection of bump-on-tail reduced electron velocity distributions at the electron foreshock boundary, *Geophys. Res. Lett.*, *11*, 496-499, 1984.

Fitzenreiter, R. J., J. D. Scudder, and A. J. Klimas, Three-dimensional analytical model for the spatial variation of the foreshock electron distribution function: Systematics and comparisons with ISEE observations, *J. Geophys. Res.*, *95*, 4155-4173, 1990.

Newman, D. L., R. M. Winglee, and M. V. Goldman, Theory and simulation of electromagnetic beam modes and whistlers, *Phys. Fluids*, *31*, 1515-1531, 1988.

Orlowski, D. S., and C. T. Russell, ULF waves upstream of the Venus bow shock: Properties of the one-Hertz waves, *J. Geophys. Res.*, *96*, 11,271-11,282, 1991.

Orlowski, D. S., and C. T. Russell, Comments on the "Electron beam excitation of upstream waves in the whistler mode frequency range" by H. K. Wong and C. W. Smith, *J. Geophys. Res.*, this issue.

Orlowski, D. S., G. K. Crawford, and C. T. Russell, Upstream waves at Mercury, Venus, and Earth: Comparison of the properties of one Hertz waves, *Geophys. Res. Lett.*, *17*, 2293-2296, 1990.

Orlowski, D. S., C. T. Russell, and R. P. Lepping, Wave phenomena in the upstream region of Saturn, *J. Geophys. Res.*, *97*, 19,187-19,199, 1992.

Orlowski, D. S., C. T. Russell, D. Krauss-Varban, and N. Omidi, On the source of upstream whistlers in the Venus foreshock, *Plasma Environments of Non-Magnetic Planets*, edited by T. I. Gombosi, pp. 217-227, Pergamon, New York, 1993.

Orlowski, D. S., C. T. Russell, D. Krauss-Varban, N. Omidi, and M. F. Thomsen, Damping and spectral formation of broadband upstream whistlers, *J. Geophys. Res.*, in press, 1995.

Scudder, J. D., A. Mangeney, C. Lacombe, C. C. Harvey, T. L. Aggson, R. R. Anderson, J. T. Gosling, G. Paschmann, and C. T. Russell, The resolved layer of a collisionless, high-β, supercritical, quasi-perpendicular shock wave, 1, Rankine-Hugonoit geometry, currents, and stationarity, *J. Geophys. Res.*, *91*, 11,019-11,052, 1986.

Sentman, D. D., M. F. Thomson, S. P. Gary, W. C. Feldman, and M. M. Hoppe, The oblique whistler instability in the Earth's foreshock, *J. Geophys. Res.*, *88*, 2048-2056, 1983.

Smith, C. W., H. K. Wong, and M. L. Goldstein, Whistler waves associated with the Uranian bow shock: Outbound observations, *J. Geophys. Res.*, *96*, 15,841-15,852, 1991.

Wong, H. K., and C. W. Smith, Electron beam excitation of upstream waves in the whistler mode frequency range, *J. Geophys. Res.*, *99*, 13,373-13,387, 1994.

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