JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. A2, PAGES 1429–1434, FEBRUARY 1, 1985

Beam-Driven Ion Cyclotron Harmonic Resonances in the Terrestrial Foreshock

CHARLES W. SMITH,[1] MELVYN L. GOLDSTEIN,[2] S. PETER GARY,[3] AND C. T. RUSSELL[4]

We report an observation of low-frequency terrestrial upstream waves which exhibit enhancements in the magnetic field power and polarization spectra at harmonics of the proton cyclotron resonance. These magnetic fluctuations exist concurrent with a "diffuse" suprathermal proton population, but a field rotation immediately following the wave observation reveals a "reflected" suprathermal distribution. We also compute instability growth rates due to this highly anisotropic "reflected" component and find relative maxima at frequencies corresponding to the enhancements in the observed spectra. We thus infer that the multiple spectral peaks are due to resonant, electromagnetic ion beam instabilities and conclude that the observed ion beam is the source of the observed upstream waves. Spectral analysis of the polarization, magnetic helicity, and minimum variance directions supports this interpretation. We find observational and theoretical evidence for both right-hand polarized waves propagating parallel to the mean magnetic field and left-hand polarized waves propagating oblique to the mean field.

1. Introduction

Early observations of upstream waves by *Greenstadt et al.* [1968] reported low-frequency magnetic fluctuations occurring upstream of, and in close proximity to, the earth's bow shock. They noted that these fluctuations occurred concurrent with "radical changes in the energy at which the main flux of particles is observed, the changes evidently resulting from a shock-connected acceleration and deceleration process." Measurements by *Fairfield* [1969] led him to suggest that these fluctuations were either super-Alfvénic whistler waves or waves produced upstream by protons streaming at two to three times the solar wind velocity. He concluded that the latter explanation was more likely, and although a one-to-one relationship between an observed ion distribution and an observed monochromatic wave event has yet to be established, most recent work on upstream waves and ions has proceeded under this hypothesis.

Observations by *Fairfield* [1969], *Scarf et al.* [1970], *Russell et al.* [1971], and *Hoppe et al.* [1981] demonstrated that the more monochromatic wave events are left-hand polarized in the spacecraft frame with a period of 10–60 s. Using ISEE 1 and ISEE 2 time lag correlations, *Hoppe et al.* [1981] further showed that these structures are propagating upstream at the Alfvén velocity. This implies that the fluctuations are right-hand polarized in the plasma frame.

Suprathermal ion events seen in association with upstream waves occur primarily in two distributions. *Asbridge et al.* [1968] observed the "reflected" distribution where the drift speed of the suprathermal population is along the magnetic field line and away from the bow shock. Drift speeds for reflected distributions are generally about twice the solar wind speed and thermal speeds (particularly parallel thermal speeds) are less than the drift speed. *Lin et al.* [1974] first observed the high-energy wing of the hotter, more isotropic "diffuse" population. Drift velocities are still away from the bow shock and parallel to the magnetic field, but the drift speed is significantly reduced, the suprathermal population being more nearly stationary in the shock frame, and thermal speeds are greatly increased [*Bonifazi and Moreno*, 1981]. *Lee* [1982] has argued that the increased thermal speeds are due to energization through multiple reflection. *Gosling et al.* [1978] were the first to note the clear distinction between the reflected and diffuse populations. *Paschmann et al.* [1979] have observed events which are intermediate between the two. An overview of upstream waves and particles may be found in *Russell and Hoppe* [1983].

All reported observations of terrestrial upstream waves have concentrated on frequencies attributable to a fundamental ($n = \pm 1$) cyclotron resonance between low-frequency waves and a field-aligned proton beam (see, for example, *Hoppe and Russell* [1983]). Theoretical discussions by *Fairfield* [1969], *Barnes* [1970], *Terasawa* [1981], and *Lee* [1982] either do not address the issue of harmonic resonances or ignore it by considering only on-axis propagation of the waves. While *Gary et al.* [1981] did consider off-axis propagation, significant harmonic growth was not found because the analysis was limited to proton distributions with isotropic temperatures and an insufficient amount of free energy to drive harmonics.

As part of their study of the Jovian foreshock, *Goldstein et al.* [1983] were the first to examine the possible role of multiple ion cyclotron harmonic resonances in the production of upstream waves. They reported spectral enhancements at 2.3, 6, 9, and 12 mHz in both the power, polarization, and cross helicity spectra. Arguing that the observed waves were the result of ion cyclotron harmonic resonances with an anisotropic proton beam (Jovian reflected distribution), they demonstrated that the linear growth rates of the harmonics can be nearly comparable to that of the fundamental resonance. This conclusion applied to both right- and left-hand polarized waves. Recently, these same observations have been attributed to harmonic excitation by relativistic electrons [*Goldstein et al*, 1985].

In this paper we analyze a terrestrial upstream wave event which demonstrates multiple, ion cyclotron harmonic resonances between the interplanetary wave population and an observed proton beam. We show that an observed bi-Maxwellian ion beam is capable of generating right- and left-hand polarized waves through ion cyclotron harmonic resonance. For our purposes, it is not necessary to address disper-

[1]Space Science Center, Department of Physics, University of New Hampshire, Durham.
[2]Laboratory for Extraterrestrial Physics, NASA/Goddard Space Flight Center, Greenbelt, Maryland.
[3]Los Alamos National Laboratory, New Mexico.
[4]Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles.

Paper number 4A8198.
0148-0227/85/004A-8198$05.00

sion effects introduced by the presence of the suprathermal ion population except in the calculation of the instability. It should be kept in mind however, that neither phase speeds nor polarizations given by the numerical solutions in section 4 are necessarily those of the standard Alfvén and fast magnetosonic waves. In section 2 we discuss the techniques and parameters employed in the data analysis, including the use of differential and band-pass filters. In section 3 an upstream wave event demonstrating multiple harmonic waves is examined. Section 4 discusses the instability analysis relevant to the ion beam observation thought to be responsible for the wave event examined in section 3.

2. DIAGNOSTIC TECHNIQUES

In this section we briefly review the parameters and spectral techniques employed in section 3. All spectra discussed are calculated from ISEE 1 magnetic field data. In order to relate these observations to spatial variations in the field, it is necessary to apply the Taylor frozen-in-flux assumption [*Taylor*, 1935]. The spectral decomposition employed allows resolution of small-scale, small-amplitude fluctuations independently from the dominant large-scale behavior. To address the possibility of low-frequency domination of the calculated high-frequency component (leakage), differential numerical filters are employed.

Spectral techniques can be susceptible to leakage when the power spectrum falls off more steeply than f^{-2} [see *Hamming*, 1983]. We are concerned with the possibility that large enhancements in the power spectrum at low frequencies may contribute to the computed high-frequency power via this process. Use of a finite impulse response (FIR) differential filter with a slope of one (prewhitening) amplifies the high-frequency power, flattens the spectrum, and thereby reduces error introduced by leakage. A differential filter was employed in the polarization and magnetic helicity analysis. It was not used to produce the power or minimum variance spectra. We use appropriately designed FIR digital filters to preserve phase information and minimize aliasing. Thus distortions are avoided in ratio parameters such as the polarization and the normalized magnetic helicity spectrum [*Matthaeus and Goldstein*, 1982]. For a discussion of FIR filter design, see *McClellan et al.* [1979]. The on-board anti-aliasing filters [*Russell*, 1978] minimize aliasing in the transmitted signal. The Nyquist frequency of the resulting time series is 0.3 Hz.

We take the normalized magnetic helicity spectrum as defined by *Matthaeus and Goldstein* [1982] to be

$$\sigma_M(k) \equiv H_M(k)/E(k) \qquad (1)$$

where

$$-1 \leq \sigma_M \leq +1$$

and $H_M(k)$ and $E(k)$ are the magnetic helicity spectrum and magnetic energy spectrum, respectively. Power and magnetic helicity spectra have been calculated using both the Blackman-Tukey and fast Fourier transform (FFT) spectral techniques (see *Matthaeus and Goldstein* [1982] for a comparison with interplanetary spectra). To demonstrate that both techniques resolve the enhancements we will be discussing in the next section, Figure 1 shows the magnetic power as computed by both methods for a 50-min period bracketing the interval shown in Figure 2. The FFT analysis employs 26 degrees of freedom and the Blackman-Tukey analysis 20. Both techniques resolve statistically significant enhancements at 30, 65, and 95 mHz with an underlying power law form. Variation

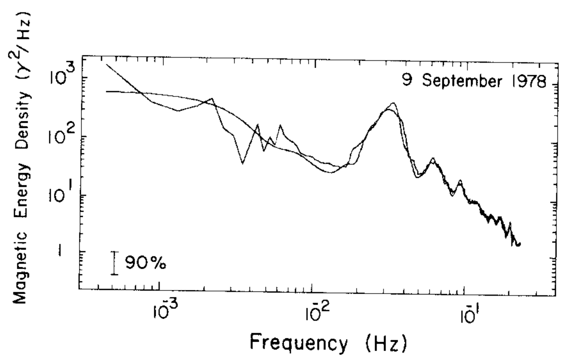

Fig. 1. Power spectra for September 9, 1978, 635:18 to 715:12 as calculated by the Blackman-Tukey and fast Fourier transform algorithms with 26 and 20 degrees of freedom, respectively. Error bar represents the 90% confidence interval for 26 degrees of freedom.

between the two techniques is well below what would be considered statistically significant. All subsequent spectral plots were produced using FFT techniques.

We will present magnetic helicity spectra as defined by (1) and will refer to σ_M as the normalized magnetic helicity. In addition to using the magnetic energy and magnetic helicity spectra to parametize the measurements, we also use the spacecraft frame polarization as defined in the minimum variance coordinates. This definition varies from the *Stix* [1962] formalism in that the "look" direction assumed by the observer is aligned with the minimum variance direction, quasi-parallel to $\mathbf{B}_0$. This is the same convention used by other authors in minimum variance analyses of upstream waves [*Russell et al.*, 1971; *Hoppe et al.*, 1981; *Hoppe and Russell*, 1983; *Goldstein et al.*, 1983; *Viñas et al.*, 1984]. The polarization is presented in spectral form and is parameterized by the degree of polarization and ellipticity (ratio of minor to major axis) with

$$-1 \leq \text{DEGPOL} \leq +1 \qquad (2)$$

where DEGPOL < 0 implies left-handed polarization, DEGPOL > 0 implies right-handed polarization, and

$$0 \leq \text{ELIP} \leq +1 \qquad (3)$$

where ELIP = 0 implies linear polarization, and ELIP = 1 implies circular polarization.

The relationship between the magnetic helicity and the spacecraft frame polarization for MHD waves is given by the product of the normalized magnetic helicity and the component of the magnetic field parallel to the solar wind velocity [*Smith et al.*, 1983]:

$$B_{0R}\sigma_M(k) > 0 \qquad (4a)$$

implies right-handed polarization in the spacecraft frame, and

$$B_{0R}\sigma_M(k) < 0 \qquad (4b)$$

implies left-handed polarization in the spacecraft frame. The corrected expression for the plasma frame polarization, incorporating the plasma frame phase velocity (assumed to be less than the solar wind speed), was derived by *Smith et al.* [1984]. The result is

$$\mathbf{V}_{ph} \cdot \mathbf{B}_0\ \sigma_M(k) > 0 \qquad (5a)$$

implies right-handed polarization in the plasma frame, and

$$\mathbf{V}_{ph} \cdot \mathbf{B}_0\ \sigma_M(k) < 0 \qquad (5b)$$

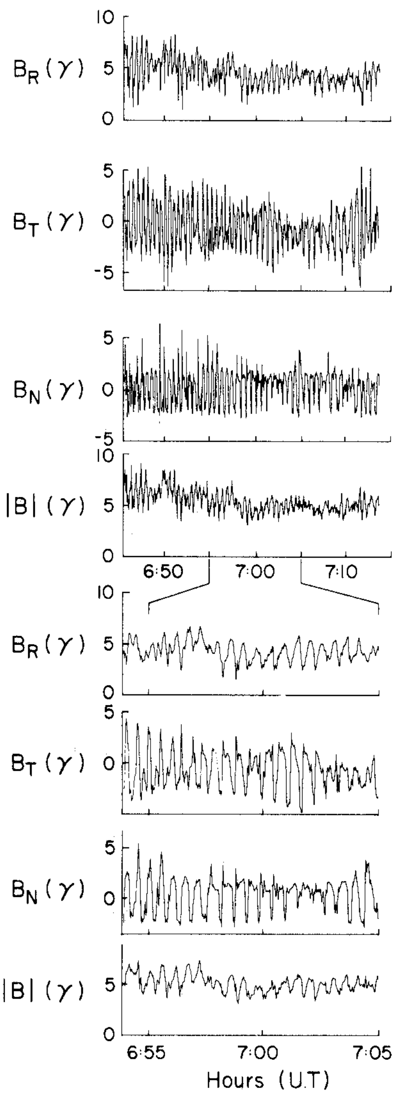

Fig. 2. Magnetic field time series for the ISEE 1 September 9, 1978, upstream wave event in heliographic (radial, tangential, normal) coordinates.

implies left-handed polarization in the plasma frame. In addition, the angle between the minimum variance direction and mean magnetic field is given, also in spectral form. Evaluation of this last quantity was performed without the use of a differential filter.

Attempts to use the plasma instrument on-board the ISEE 1 spacecraft to resolve solar wind fluid velocity fluctuations on the time scale of the waves have proven ineffective (J. Gosling, private communication, 1984), and determination of the cross helicity [*Smith et al.*, 1983; *Goldstein et al.*, 1983] has not been possible. We estimate the possible compression of these waves by computing the power spectrum of the magnitude of the magnetic fluctuations. This is an acceptable measurement of the compression when it may be assumed that only linear, cold plasma waves are present. It is less acceptable when applied to systems with strong nonlinearities. *Goldstein et al.* [1983] have demonstrated a strong correlation between the field magnitude and density variations in the study of Jovian waves similar to those examined here.

3. Wave Observation

In this section we examine the September 9, 1978, period of upstream wave activity presented in Figure 2. The data interval begins 0645:24 when ISEE 1 is at (18.7, 10., 5.8) R_E in the usual XYZ earth-centered GSE coordinates and ends 0713:13. The analysis employs 54 degrees of freedom in an effort to resolve an otherwise poorly determined 30-mHz polarization.

The mean magnetic field during this period was (4.75, −0.42, 0.45) γ in heliographic RTN coordinates, the solar wind speed was 475 km/s, and the average density ranged from 15 protons/cm^3 at the beginning of the period to 8 protons/cm^3 at the end. The ambient proton temperature was 5×10^4 °K and the ambient electron temperature was 2×10^5 °K. The Los Alamos fast plasma analyzer observed a weak diffuse ion event during this period (M. L. Thomsen, private communication, 1984). The NOAA/APL high-energy particle analyzer reports no high-energy electron anisotropy (D. Mitchell, private communication, 1984).

The magnetic field power spectrum (upper trace in Figure 3*a*, now plotted on a log-linear scale) displays enhancements

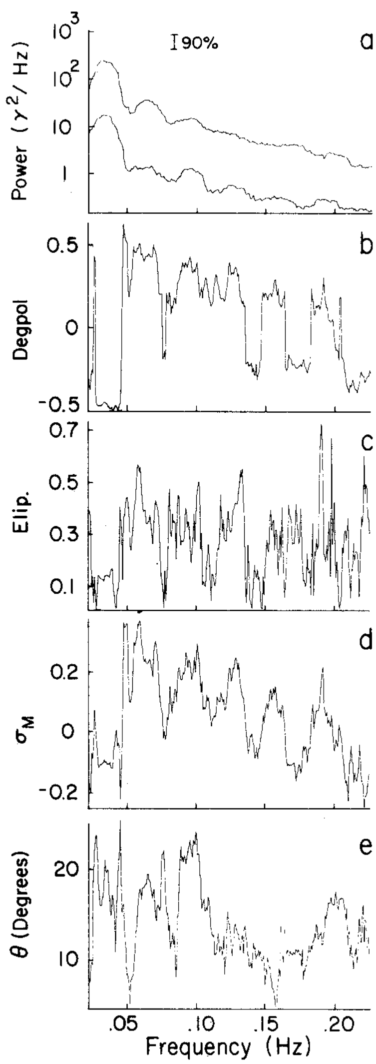

Fig. 3. September 9, 1978, 0645:24 to 0713:13 (*a*) power in *B* and power in |*B*|, (*b*) degree of polarization, (*c*) ellipticity, (*d*) magnetic helicity, and (*e*) angle between mean field and minimum variance direction. Figures 3*b*, 3*c* and 3*d* were prewhitened. All have 54 degrees of freedom.

at 30, 65, and 95 mHz. Power in the magnitude of the field (lower trace in Figure 3*a*) indicates that all three regions are compressive. Polarization measurements (Figures 3*b* and 3*c*) indicate the 30-mHz signal to be left-hand polarized in the spacecraft frame with the degree of polarization equal to +0.5 and an ellipticity of 0.14. The 65- and 95-mHz signals are right-hand polarized in the spacecraft frame with degree of polarization −0.45 and −0.33 and ellipticities of 0.35 and 0.30, respectively.

If we assume that the waves are propagating upstream at speeds less than the solar wind speed, as is typical of other upstream wave observations at earth and Jupiter [*Hoppe and Russell*, 1983; *Smith et al.*, 1983; *Goldstein et al.*, 1983], then the magnetic helicity (Figure 3*d*) indicates that the plasma frame polarization of the 30-, 65-, and 95-mHz signals are right, left, and left, respectively.

A minimum variance analysis indicates that the 65- and 95-mHz waves are propagating off-axis. The 30-mHz wave is more field aligned. However, there is sufficient fluctuation in the mean field to render suspect the interpretation of a minimum variance analysis. Since the mean field observed by the waves is probably meaningful only when calculated over a few wavelengths, and since this mean field fluctuates by 20 degrees over the duration of the observation, we will use the minimum variance analysis to suggest only that the 65- and 95-mHz waves are propagating further off-axis than is the 30-mHz wave.

The compressive nature of the waves (demonstrated by the field magnitude spectrum displayed in the lower trace of Figure 3*a*) is consistent with the off-axis propagation which is measured for the 65- and 95-mHz enhancements (Figure 3*e*). A compressive wave at 30 mHz with a field-aligned minimum variance direction is not expected from small-amplitude wave theory.

An alternate interpretation of the wave data is possible and should be presented. Early discussion of low-frequency upstream waves considered the possibility that the fluctuations were not locally generated, Doppler-shifted MHD waves, but rather, they might be right-hand polarized whistler waves propagating upstream at approximately the solar wind speed. This interpretation was rejected by *Fairfield* [1969] as an unlikely explanation for the class of low-frequency wave observations which spans a wide range in solar wind parameters and field orientation and was further disputed by the two spacecraft correlation studies of *Hoppe and Russell* [1983]. However, we cannot neglect the possibility that this particular observation may in fact represent whistler activity. If this is true, then the 65- and 95-mHz waves which are observed to be right-hand polarized in the spacecraft frame must be propagating upstream faster than the solar wind speed. The 30-mHz wave which is observed to be left-hand polarized in the spacecraft frame must have a phase speed that is less than the solar wind speed, in order that it be a right-hand polarized wave in the plasma frame. This implies local generation. The inability of the ISEE 1 spacecraft to adequately resolve solar wind fluid velocity fluctuations on this time scale prevents us from answering this issue. In the next section we show that the locally generated MHD wave interpretation is consistent with the subsequently observed proton distribution.

4. ELECTROMAGNETIC ION BEAM INSTABILITY ANALYSIS

Ion beam instabilities have been frequently credited as the source of MHD waves in the vicinity of shocks. In this context

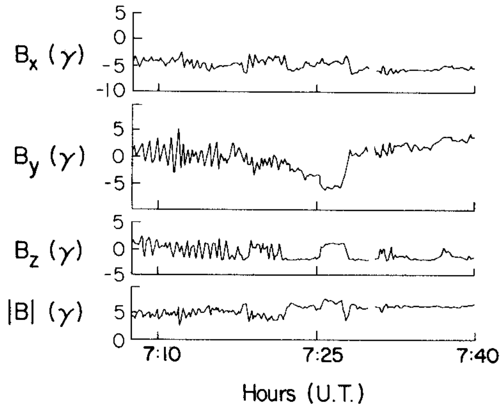

Fig. 4. Magnetic field time series in earth-centered GSE coordinates showing the rotation of the interplanetary magnetic field which marks the end of the wave event discussed in section 3. This rotation coincides with the observation of the field-aligned proton beam discussed in section 4.

they have been discussed by *Barnes* [1970], *Montgomery et al.* [1975, 1976], *Gary et al.* [1981], *Sentman et al.* [1981], and *Viñas et al.* [1984]. They have also been discussed within an astrophysical context by *Tademaru* [1969].

Tademaru and Barnes used the small growth rate approximation to compute a growth rate based on the assumption that the real part of the wave frequency is given by the cold plasma dispersion equation in the absence of a beam. *Montgomery et al.* [1975, 1976], *Gary* [1978], *Gary et al.* [1981], and *Sentman et al.* [1981] obtained complete numerical solutions of the Vlasov dispersion equation and showed that the presence of even a weak beam led to significant changes in the dispersion relations for these instabilities. However, none of these authors used beam parameters appropriate for the generation of harmonic waves. *Goldstein et al.* [1983] gave the first demonstration that ion beams with high thermal anisotropy can drive significant off-axis growth through the ion cyclotron harmonic resonances at

$$\omega = \mathbf{k} \cdot \mathbf{v}_{0b} \pm n\Omega_p \tag{6}$$

where ω is the wave frequency, $\mathbf{k}$ is the wave vector, $\mathbf{v}_{0b}$ is the beam drift velocity, and Ω_p is the proton gyrofrequency.

In this section we compute the instability growth rate, γ, based on an observed ion distribution function. We use the code of *Forslund et al.* [1979], which solves the electromagnetic Vlasov dispersion equation without the approximations previously discussed. Recent work by *Gary et al.* [1984] and *Goldstein et al.* [1985] attempts to bring the general drift instability analysis into the parameter regime appropriate to terrestrial and Jovian upstream waves, respectively. We refer the reader to these references for a detailed discussion of the possible electromagnetic particle beam instabilities and the dependence of harmonic wave generation upon beam parameters. In this section we present only one relevant solution and continue to quote computed polarizations as defined in section 2.

The wave observation discussed in section 3 ends with a field rotation which places the spacecraft closer to the upstream foreshock boundary. This field rotation is shown in Figure 4. At this time the weak, relatively hot diffuse ion population disappears, and an anisotropic, relatively cold reflected population is observed. Some of the parameters of this population (particularly the beam temperature) are observed

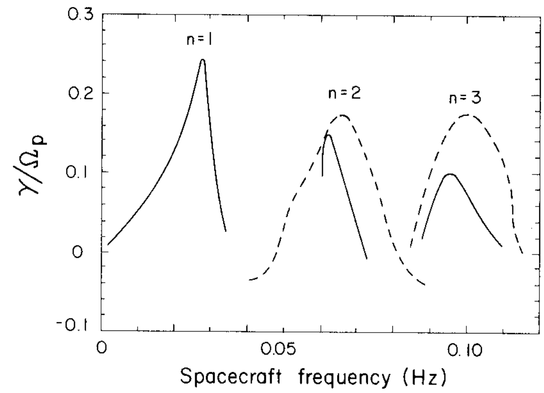

Fig. 5. Growth rates in units of the proton cyclotron frequency for beam instability as a function of spacecraft frequency. The solid curve is right-hand polarized and the dashed curve is left-hand polarized. Propagation directions are as stated in Table 1.

to fluctuate and it is not appropriate to claim that one parameterization adequately represents the entire period. However, the range of parameters observed is consistently capable of generating multiple waves, with only the polarization of the harmonics in question. We therefore choose one observed parameterization for the purpose of demonstration and acknowledge that the observed waves must result from the sum of the observed beam parameters.

We choose the parameters of the ion beam observed by the joint Los Alamos/Max-Planck-Institut fast plasma experiment on ISEE 1 on September 9, 1978, from 0724:37.94 to 0724:40.5. Only an ion beam is observed during the period following the waves, and the plausible high-energy electron population which could also resonate with the observed waves is not observed (D. Mitchell, private communication, 1984). At this time, the beam represented 2.4% of the proton density (8 protons/cm^3) with a plasma frame drift velocity of 1050 km/s directed along the magnetic field and away from the shock. The temperature of the beam parallel to the field was 58 eV and the perpendicular temperature was 1.1 keV.

When beam densities and drift speeds are this large (the drift speed is 51 times the ambient proton thermal speed) and beam thermal speeds are sufficiently modest, the resulting wave modes (both stable and unstable) are drastically different from zero beam results. Indeed, the terms "fast magnetosonic" and "Alfvén" can be used only in that the observed wave modes map back into the familiar cold plasma modes as the beam is reduced.

Figure 5 shows the growth rate of the forward propagating right- and left-hand polarized modes for the selected angles of propagation where growth rates are maximum. Frequencies are given in the spacecraft frame. The right-hand mode (solid line) demonstrates clear harmonic structure for $n = 1$, 2, and 3. The forward propagating left-hand mode (dashed line) demonstrates harmonic growth for $n = 2$ and 3 which exceeds the growth of the right-hand mode at these frequencies. The fundamental, $n = 1$, left-hand resonance is not observed to be unstable. A greater beam temperature with a significant population of backward traveling particles would be needed to produce significant growth rates for this mode [*Gary et al.*, 1984].

The $n > 1$ right- and left-hand resonances do not compete at the same wave numbers, or even at the same values of $\mathbf{k} \cdot \mathbf{B}_0$ as might be inferred from Figure 5. Table 1 gives the growth rates, plasma frame frequencies, wave numbers, propagation angles, plasma frame velocities, and spacecraft frame frequencies for the five peak growth rates displayed in Figure 5. It is clear from this that the left-hand mode is unstable at greater angles to the mean field and at lesser values of $\mathbf{k} \cdot \mathbf{B}_0$ than is the right-hand mode. The two modes are observed at the same spacecraft frequencies because the propagation speed of the right-hand mode is enhanced by its growth, thus reducing the effect of the solar wind Doppler shift [*Lee*, 1982; *Goldstein et al.*, 1983; *Gary et al.*, 1984]. The polarizations listed in Table 1 are defined in the minimum variance coordinate system. This is the same definition that was employed in the data analysis of section 3. The parameter a is the gyroradius of an ambient thermal proton.

The growth rates, spacecraft frequencies, propagation directions, and polarizations given in Figure 5 and Table 1 accurately reflect the observed wave spectra. The predicted waves propagate parallel to the beam drift velocity (as opposed to antiparallel) as was assumed in the polarization analysis in section 3. Backward propagating waves are less unstable in this parameter regime. The anisotropy instability is stabilized by the high drift speed, while the growth rate of the right-hand, nonresonant instability is exceeded by the resonant instability [see *Gary et al.*, 1984]. The wave enhancements are predicted and observed to be right-, left-, and left-hand polarized at 30, 65, and 95 mHz, respectively, and the 30-mHz on-axis wave is seen to have the greatest growth rate.

5. SUMMARY

We have presented an interval of magnetic field fluctuations which was observed in the terrestrial foreshock by ISEE 1. This period demonstrated multiple, evenly spaced enhancements over narrow frequency bands in the wave power, magnetic helicity, and polarization spectra, thereby suggesting the source to be ion cyclotron harmonic resonance with an ion beam. Concurrent with the waves was a weak diffuse population of suprathermal protons which is not likely to produce the narrow frequency bands of the observed waves. A field rotation marking the end of the wave observation carried the spacecraft closer to the foreshock's upstream boundary where a reflected population of suprathermal protons was observed. Using the parameters of this cold ion beam in a fully electromagnetic linear dispersion code, we were able to account for the observed spacecraft frequency of the waves, the observed polarizations, and the anticipated upstream propagation direction. We therefore suggest that the waves resulted from instabilities at ion cyclotron harmonic resonances with the observed reflected ion distribution. The observation of a diffuse population, rather than a reflected population, at the same time that the waves are present is in keeping with particle pitch-angle scattering calculations [*Lee and Skadron*, 1985; *Winske and Leroy*, 1984] and observations [*Paschmann et al.*,

TABLE 1. Attributes of Maximum Growth Rate for Resonances Shown in Figure 5

n	Mode	Ka	$\gamma/\Omega p$	$\omega/\Omega p$	Angle, deg	Polarization	Spacecraft Frequency, $\times 10^{-2}$ Hz
1	right	0.035	0.246	0.2144	0	+1.00	2.7
2	right	0.10258	0.15103	0.2786	48.7	+0.65	6.2
3	right	0.15557	0.0989	0.3533	50.2	+0.55	9.4
2	left	0.14808	0.17435	0.0466	67.7	−0.68	6.5
3	left	0.21272	0.17608	0.0332	66.7	−0.74	9.8

1979] and does not preclude the results of this instability analysis.

Acknowledgments. The authors would like to thank W. H. Matthaeus, M. A. Lee, and F. M. Ipavich for many helpful discussions. The authors are particularly indebted to M. M. Mellott, whose familiarity with ISEE observations fascilitated the selection of data intervals, and M. F. Thomsen, who supplied the needed background and suprathermal plasma parameters. We also acknowledge D. W. Forslund's permission to use his linear dispersion equation code. This work was supported in part by an ISEE Guest Investigator grant to the University of New Hampshire and NASA Solar Terrestrial Theory Program grants to both the University of New Hampshire, Los Alamos National Laboratory, and Goddard Space Flight Center.

The editor thanks E. W. Greenstadt and another referee for their assistance in evaluating this paper.

REFERENCES

Asbridge, J. R., S. J. Bame, and I. B. Strong, Outward flow of protons from the earth's bow shock, *J. Geophys. Res.*, *73*, 5777, 1968.

Barnes, A., Theory of generation of bow-shock-associated waves in the upstream interplanetary medium, *Cosmic Electrodyn.*, *1*, 90, 1970.

Bonifazi, C., and G. Moreno, Reflected and diffuse ions backstreaming from the earth's bow shock, 1, Basic properties, *J. Geophys. Res.*, *86*, 4397, 1981.

Fairfield, D. H., Bow shock associated waves observed in the far upstream interplanetary medium, *J. Geophys. Res.*, *74*, 3541, 1969.

Forslund, D. W., J. M. Kindel, and M. A. Stroscio, Current driven electromagnetic ion cyclotron instability, *J. Plasma Phys.*, *21*, 127, 1979.

Gary, S. P., The electromagnetic ion beam instability and energy loss of fast alpha particles, *Nucl. Fusion*, *18*, 327, 1978.

Gary, S. P., J. T. Gosling, and D. W. Forslund, The electromagnetic ion beam instability of the earth's bow shock, *J. Geophys. Res.*, *86*, 6691, 1981.

Gary, S. P., C. W. Smith, M. A. Lee, M. L. Goldstein, and D. W. Forslund, Electromagnetic ion beam instabilities, *Phys. Fluids*, *27*, 1852, 1984.

Goldstein, M. L., C. W. Smith, and W. H. Matthaeus, Large-amplitude MHD waves upstream of the Jovian bow shock, *J. Geophys. Res.*, *88*, 9989, 1983.

Goldstein, M. L., H. K. Wong, A. F. Viñas, and C. W. Smith, Large-amplitude MHD waves upstream of the Jovian bow shock: Reinterpretation, *J. Geophys. Res.*, *90*, 302, 1985.

Gosling, J. T., J. R. Asbridge, S. J. Bame, G. Paschmann, and N. Sckopke, Observations of two distinct populations of bow shock ions, *Geophys. Res. Lett.*, *5*, 957, 1978.

Greenstadt, E. W., I. M. Green, G. T. Inoye, A. J. Hundhausen, S. J. Bame, and I. B. Strong, Correlated magnetic field and plasma observations of the earth's bow shock, *J. Geophys. Res.*, *73*, 51, 1968.

Hamming, R. W., *Digital Filters*, Prentice-Hall, Englewood Cliffs, N. J., 1983.

Hoppe, M. M., and C. T. Russell, Plasma rest frame frequencies and polarizations of the low-frequency upstream waves: ISEE 1 and 2 observations, *J. Geophys. Res.*, *88*, 2021, 1983.

Hoppe, M. M., C. T. Russell, L. A. Frank, T. E. Eastman, and E. W. Greenstadt, Upstream hydromagnetic waves and their association with backstreaming ion populations: ISEE 1 and 2 observations, *J. Geophys. Res.*, *86*, 4471, 1981.

Lee, M. A., Coupled hydromagnetic wave excitation and ion acceleration upstream of the earth's bow shock, *J. Geophys. Res.*, *87*, 5063, 1982.

Lee, M. A., and G. Skadron, A simple model for the formation of "reflected," "intermediate," and "diffuse" ion distributions upstream of the earth's bow shock, *J. Geophys. Res.*, *90*, 39, 1985.

Lin, R. P., C.-I. Meng, and K. A. Anderson, 30- to 100-keV protons upstream from the earth's bow shock, *J. Geophys. Res.*, *79*, 489, 1974.

Matthaeus, W. H., and M. L. Goldstein, Measurement of the rugged invariants of magnetohydrodynamic turbulence in the solar wind, *J. Geophys. Res.*, *87*, 6011, 1982.

McClellan, J. H., T. W. Parks, and L. R. Rabiner, FIR linear phase filter design program, in *Programs for Digital Signal Processing*, IEEE Press, New York, 1979.

Montgomery, M. D., S. P. Gary, D. W. Forslund, and W. C. Feldman, Electromagnetic ion-beam instabilities in the solar wind, *Phys. Rev. Lett.*, *35*, 667, 1975.

Montgomery, M. D., S. P. Gary, W. C. Feldman, and D. W. Forslund, Electromagnetic instabilities driven by unequal proton beams in the solar wind, *J. Geophys. Res.*, *81*, 2743, 1976.

Paschmann, G., N. Sckopke, S. J. Bame, J. R. Asbridge, J. T. Gosling, C. T. Russell, and E. W. Greenstadt, Association of low-frequency waves with suprathermal ions in the upstream solar wind, *Geophys. Res. Lett.*, *6*, 209, 1979.

Russell, C. T., The ISEE 1 and 2 fluxgate magnetometers, *IEEE Trans. Geosci. Electron.*, *GE-16*, 239, 1978.

Russell, C. T., and M. M. Hoppe, Upstream waves and particles, *Space Sci. Rev.*, *34*, 115, 1983.

Russell, C. T., D. D. Childers, and P. J. Coleman, Jr., Ogo 5 observations of upstream waves in the interplanetary medium: Discrete wave packets, *J. Geophys. Res.*, *76*, 845, 1971.

Scarf, F. L., R. W. Fredericks, L. A. Frank, C. T. Russell, P. J. Coleman, Jr., and M. Neugebauer, Direct correlations of large-amplitude waves with suprathermal protons in the upstream solar wind, *J. Geophys. Res.*, *75*, 7316, 1970.

Sentman, D. D., J. P. Edmiston, and L. A. Frank, Instabilities of low frequency, parallel propagating electromagnetic waves in the earth's foreshock region, *J. Geophys. Res.*, *86*, 7487, 1981.

Smith, C. W., M. L. Goldstein, and W. H. Matthaeus, Turbulence analysis of the Jovian upstream "wave" phenomenon, *J. Geophys. Res.*, *88*, 5581, 1983.

Smith, C. W., M. L. Goldstein, W. H. Matthaeus, and A. F. Viñas, Correction to "Turbulence analysis of the Jovian upstream 'wave' phenomenon," *J. Geophys. Res.*, *89*, 9159, 1984.

Stix, T. H., *The Theory of Plasma Waves*, McGraw-Hill, New York, 1962.

Tademaru, E., Plasma instabilities of streaming cosmic rays, *Astrophys. J.*, *185*, 959, 1969.

Taylor, G. E., Statistical theory of turbulence, *Proc. R. Soc. London Ser. A*, *151*, 421, 1935.

Terasawa, T., Energy spectrum of ions accelerated through Fermi process at the terrestrial bow shock, *J. Geophys. Res.*, *86*, 7595, 1981.

Viñas, A. F., M. L. Goldstein, and M. H. Acuña, Spectral analysis of magnetohydrodynamic fluctuations near interplanetary shocks, *J. Geophys. Res.*, *89*, 3762, 1984.

Winske, D., and M. M. Leroy, Diffuse ions produced by electromagnetic ion beam instabilities, *J. Geophysical Res.*, *89*, 2673, 1984.

S. P. Gary, Group ESS-8, Mail Stop D438, Los Alamos National Laboratory, Los Alamos, NM 87545.

M. L. Goldstein, Laboratory for Extraterrestrial Physics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

C. T. Russell, Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024.

C. W. Smith, Space Science Center, Department of Physics, University of New Hampshire, Durham, NH 03824.

(Received June 11, 1984;
revised October 22, 1984;
accepted October 23, 1984.)