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ISEE-3 WAVE MEASUREMENTS IN THE DISTANT GEOMAGNETIC TAIL AND BOUNDARY LAYER

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Abstract. The ISEE-3 excursion into the distant tail region reveals a complex structure with several wave, particle and field characteristics that differ significantly from those measured closer to earth. The most striking results are found within the distant boundary layer where intense electrostatic turbulence levels are detected in association with bi-directional electron distributions. The wave amplitudes appear to increase with increasing downstream distance and the polarizations are those expected for ion acoustic oscillations. Near the boundary of the distant plasmas sheet the turbulence spectra are essentially identical to those measured much closer to earth on IMP-8. We also find that in the distant tail the continuum radiation spectrum has a low frequency cutoff that is much higher than the minimum value for the local plasma frequency.

Introduction

The decision to move ISEE-3 from its position near the upstream libration point to the distant geomagnetic tail was based on the expectation that important new plasma physics phenomena would be detected in the region beyond the lunar orbit. From the point of view of plasma processes, the ISEE-3 wave observations have a special role because no instrument of this type was carried on Explorer 33 or on Explorer 35 to explore even the near-earth tail region out to 80 Re. Pioneer-8 did have a very rudimentary wave capability that helped to illuminate the structure of the distant geomagnetic tail and wake at a downstream distance of about 500 Re (Scarf et al., 1970; Siscoe et al., 1970), but these measurements could not provide information on interaction phenomena. In terms of comprehensive studies of wave-particle interactions in the earth's tail, the most valuable measurements to date have come from the earth orbiter, IMP-8 (Gurnett et al., 1976) [the IMP-7 wave instrument (Scarf et al., 1974; Coroniti et al., 1977) also gave limited data in the region out to 35 Re]. ISEE-3 has now provided the first real opportunity to study wave phenomena in the geomagnetic tail beyond 40 Re, the apogee of IMP-8.

Wave, Particle and Field Observations

Slavin et al. (1983) recently described in detail the ISEE-3 trajectory and average magnetic field configuration for the first relatively close-in traversal of the tail ($r < 94$ Re) and for the first deep excursion to $r = 225$ Re. In another recent report, Bame et al. (1983) presented initial results from the ISEE-3 plasma analyzer, and they showed that all plasma regimes identified from earlier measurements (plasma sheet, low latitude boundary levels, mantle, lobe and magnetosheath) remained recognizable in the distant tail, although the regimes appeared to be "intermingled" far from earth, and a well-defined low density tail lobe was rarely encountered. The distant tail plasma was also characterized by unusually large flow speeds (generally tailward) and by the very common presence of bi-directional electron distribution functions.

Bame et al. selected two twelve-hour intervals on January 24, 27, 1983 to illustrate their general results, and we use these same periods for the initial detailed comparison of wave, particle and field observations. The bottom panel in Figure 1 shows the magnetic field profile for the first twelve hours on January 24, and the next three panels show the variation in electron temperature, flow speed and plasma density. The coded bar above the density display indicates the various regimes as determined by the plasma probe; magnetosheath (MS), boundary layer (BL), plasma sheet (PS) and lobe (L). In this report, and in Bame et al., the term boundary layer refers to plasma within the tail lobe directly adjacent to the magnetopause and magnetosheath.

The ISEE-3 plasma wave instrument has a sixteen channel spectrum analyzer to measure electric fields over the frequency range 17 Hz to 100 kHz (two samples per channel per second), and an eleven channel analyzer to measure magnetic fields over the range 0.3 Hz to 1 kHz (at lower sampling rates). The upper panels in Figure 1 show peak (line) and average (solid black) wave amplitudes from 19 of the 27 channels (96 second accumulation intervals). For the E-field panels each amplitude plot is logarithmic with a total top-to-bottom range of almost five orders of magnitude; the vertical scale for each B-field channel is on the order of three orders of magnitude.

The plasma wave modes are identified by comparing observations with local values of characteristic plasma frequencies. In order to facilitate this comparison, we plot directly on Figure 1 the profiles for the electron cyclotron frequency, fc, and the electron plasma frequency, fp. For f < fc, Figure 1 shows wave activity that we generally interpret in terms of detection of whistler mode turbulence. The magnetosheath is characterized by intense electromagnetic wave levels, and the lowest frequency spectral components have relatively diffuse amplitude varia-

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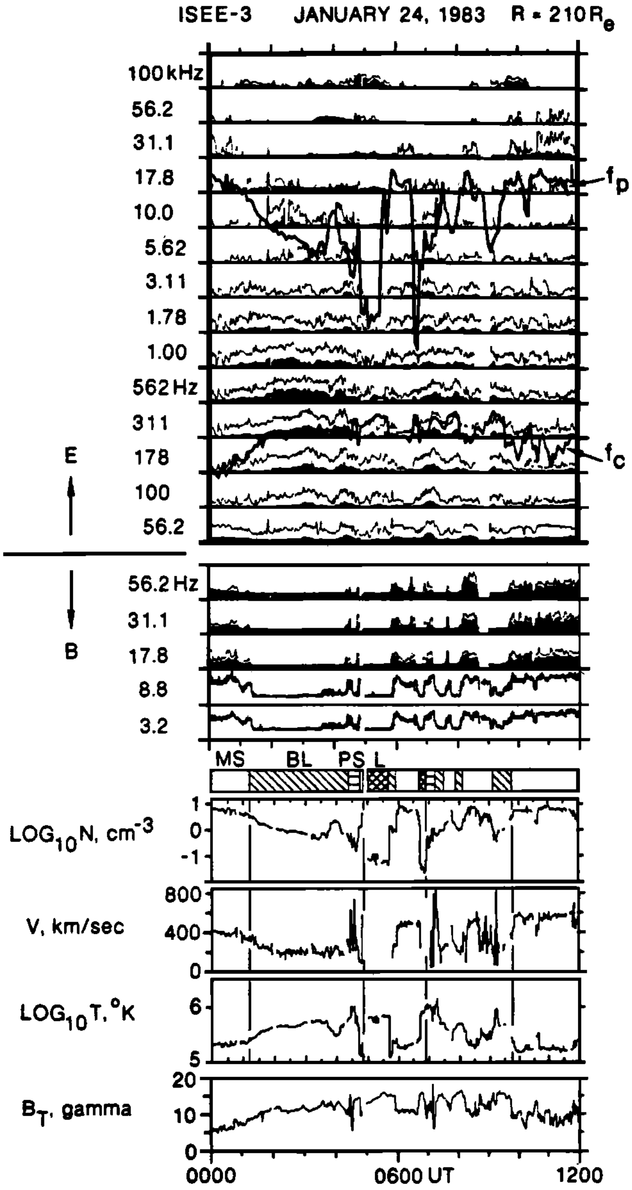

Fig. 1. Plasma wave measurements, magnetic field profile and plasma parameters for a twelve hour period in which there were several crossings from the magnetosheath (MS) to the boundary layer (BL), the plasma sheet (PS) and the tail lobe (L). Here fp represents the electron plasma frequency and fc is the electron cyclotron frequency.

tions across the magnetopause similar to those detected on IMP-7 near 35 Re (Scarf et al., 1974). Figure 1 also shows electromagnetic noise bursts localized near the boundary of the plasma sheet, but, as on IMP-8 (Gurnett et al., 1976) these whistler mode signals are detected in association with electric field oscillations having a broadbanded turbulence spectrum extending up to several kHz.

At the highest frequencies, many of the ISEE-3 plasma wave measurements in the distant tail are similar to those detected closer to earth. Auroral kilometric radiation primarily appears in the 100 kHz channel of Figure 1 and a Type III solar radio burst starting at about 0315 is evident in the 56 kHz panel. As noted by Gurnett (1974), the measurements of kilometric radiation in the near-tail have provided useful indications of auroral and magnetospheric substorm activity (see also Gurnett et al., 1976; Voots et al., 1977; Green et al., 1979). This correspondence persists in the distant tail as well; on January 24, well-defined substorm onsets at 0440 and at 0820 (D. Baker, private communication, 1983) are associated with onsets of 100 and 56 kHz radiation on ISEE-3. At lower frequencies (31.1, 17.8, 10 and 5.6 kHz) we identify the steady signals with high peak to average ratios as electron plasma oscillations or upper hybrid resonance emissions.

Figure 1 shows that when ISEE-3 was in the tail lobe, the local plasma frequency was as low as 2 kHz, but in this low density region, no continuum radiation was detected in the 3.1 kHz channel and, in fact, it was barely detectable at 5.6 kHz. At Jupiter, the Voyager 1,2 plasma wave investigators (Scarf et al., 1979; Gurnett et al., 1979) showed that throughout the encounters the continuum radiation spectrum clearly extended down to the local value for fp, and in the region out to about 6000 Rj, the lower limit of the continuum spectrum was generally used to deduce absolute values for the plasma density (Gurnett et al., 1980; Scarf et al., 1981; Kurth et al., 1982). Thus, the result displayed in Figure 1 suggests that the continuum radiation generation mechanisms at earth and at Jupiter have significant differences.

The most striking new result on January 24 involves the boundary layer traversal between 0125 and 0430. It can be seen that here the wave instrument detected intense electric field signals with f > fc, while the search coil recorded essentially no whistler mode magnetic activity, although large amplitude ultra-low frequency waves were detected in portions of the boundary layer by the DC magnetometer (Tsurutani and Smith, 1983). The absence of low frequency whistler turbulence within the boundary layer clearly distinguishes this region from the magnetosheath and plasma sheet, and we note that the boundary layer wave phenomena have no real counterpart in any near-earth observations (Rodriguez (1979) did point out that E-field wave activity with f > fc is a regular component of magnetosheath turbulence close to earth, but here the full spectrum involves intense whistler mode turbulence as well).

ISEE-3 also had four brief traversals of the boundary layer on January 29, and in each case it was found that this layer was characterized by the presence of low flow speeds and intense high frequency electric turbulence along with the absence of low frequency electromagnetic wave activity. Detailed comparisons with the color-coded electron spectrograms of Bame et al. (1983) show that the most intense boundary wave levels are detected in association with electron distributions that are clearly bi-directional.

Wave Mode Analysis

In order to study the variation of the mid-frequency electrostatic wave turbulence with increasing downstream distance, we searched through the ISEE-3 measurements from the first tail passage (R = 70-95 Re) for similar boundary layer conditions. J. Gosling identified close-in regions which had plasma flow speeds, densities and bi-directional distributions similar to those found in the distant boundary layer, and his tabulations enabled us to perform first order radial gradient studies. A typical result is shown in the upper panel of Figure 2. This demonstrates that the boundary layer spectral characteristics change dramatically with penetration into the deep tail. The deep tail spectral characteristics (elevated averages, amplitude peaks in channels for which f exceeds fc) only began to be evident when we examined data records with R > 180 Re.

The lower panel in Figure 2 illustrates the variation with R of broadband noise associated with the plasma sheet in the tail. The IMP-8 (Gurnett et al., 1976) and the ISEE-3 spectra are both typical of measurements during periods of relatively high intensity and this figure suggests a surprising absence of any radial gradient, or even a long term temporal variation. We have also found that the continuum radiation spectra measured on IMP-8 and on ISEE-3 are quite similar.

Since the boundary layer waves detected on ISEE-3 represent new phenomena that appear to intensify significantly in the deep tail, it is of considerable interest to try to identify the oscillation mode or modes. Figure 1 clearly shows that the highest intensities appear in channels with f > fc, and this fact suggests that some of the observations might involve the (n + 1/2) fc electron cyclotron harmonic modes first discussed by Kennel et al. (1970). Another plausible possibility involves Doppler-shifted ion acoustic waves, which would have impulsive amplitude characteristics (high peak-to-average ratios) and broad spectra, as observed. Unfortunately, the ISEE-3 wave instrument does not have the high resolution broadband waveform capability that can generally provide unambiguous wave mode identification.

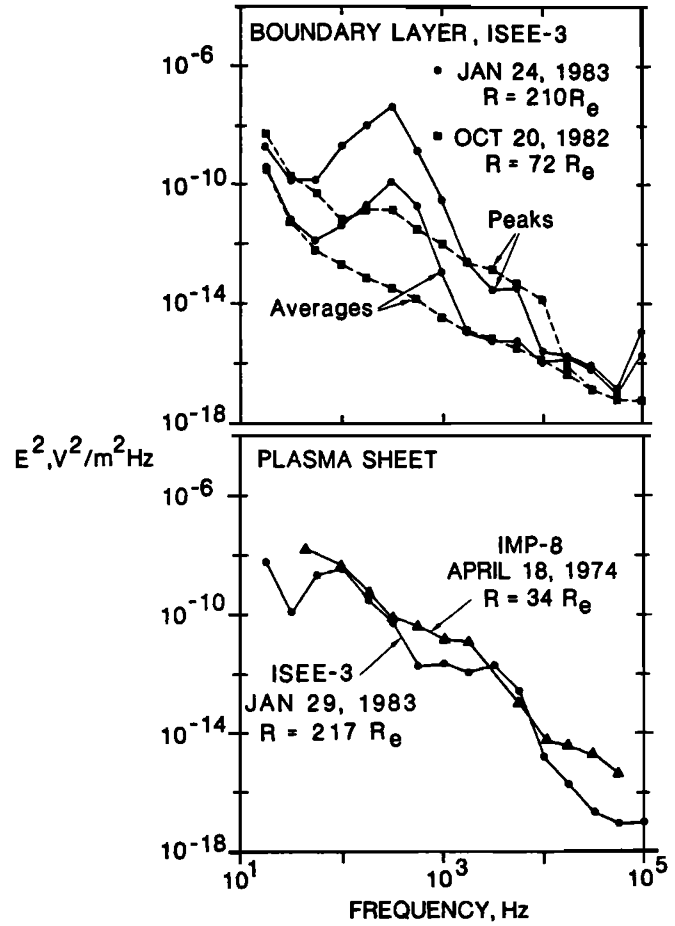

Fig. 2. Top: Variation with radial distance of electric field spectra in the boundary layer. Bottom: Comparison of IMP-8 and ISEE-3 electric field spectra associated with the plasma sheet. The plasma variations on January 29, 1983, are described in detail by Bame et al. (1983).

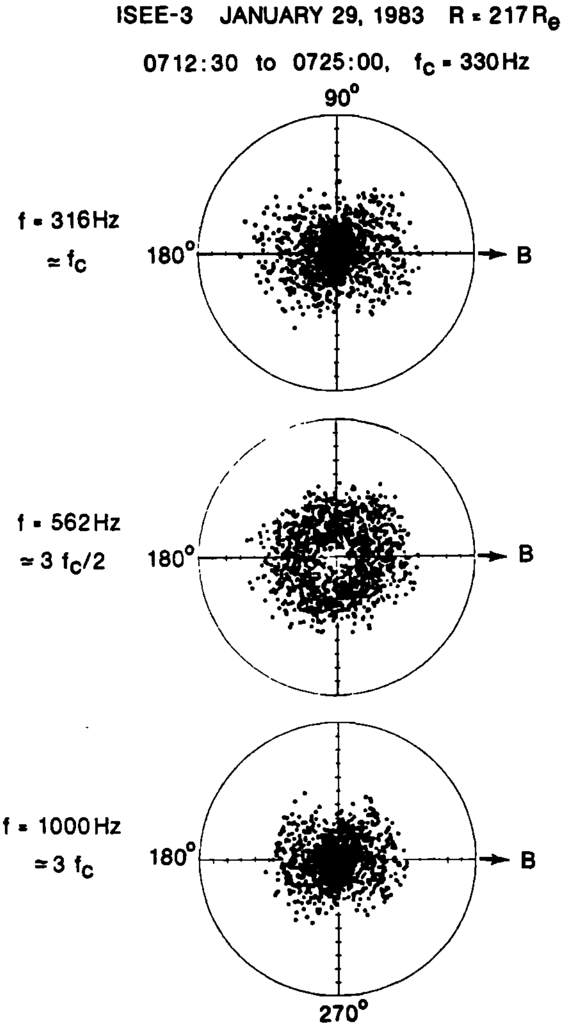

Fig. 3. Polarizations of boundary layer waves. As described in the text, we interpret the weak polarization parallel to B (for f = n fc, n = 1,3) as evidence that the waves are Doppler-shifted ion acoustic oscillations.

A significant plasma mode signature involves the wave polarization with respect to the magnetic field, and Figure 3 contains such a polarization plot for a 12.5 minute portion of a boundary layer traversal on January 29, 1983. If the waves were (n + 1/2) fc oscillations, then we would expect the highest amplitudes to be detected when the antenna was perpendicular to the magnetic field (Kennel et al., 1970) while for ion acoustic oscillations, the peaks would occur with the antenna parallel to B, except for frequencies corresponding to the electron cyclotron half harmonics where mode coupling could yield isotropy. Since the boundary layer turbulence is quite impulsive (with high peak-to-average ratios), we cannot expect any clear-cut polarization pattern, but Figure 3 does indeed suggest a field-aligned distribution for those channels with f = n fc (n = 1,3) and a relatively isotropic distribution for the channel with f = 3fc/2. Thus, the angular distributions appear to be consistent with an ion acoustic wave explanation for the boundary layer turbulence.

Discussion

The ISEE-3 identification of ion acoustic waves in the magnetosphere boundary layer implies that the plasma in this region is significantly non-Maxwellian. These waves can be associated with ion beams, currents, or heat flux instabilities, and the growth rates are enhanced if Te/Ti >> 1. Although the ion portion of the ISEE-3 plasma probe is not operative, other instruments on the spacecraft give information on the suprathermal ion distributions and on the higher mass species, and future investigations of this topic will involve multi-instrument correlations.

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