Abstract. The ISEE-3 excursion into the distant geomagnetic 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 plasma 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 (1 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, $f_c$, and the electron plasma frequency, $f_p$. For $f < f_c$, 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-
Scarf et al.: ISEE-3 Wave Measurements

Figure 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.

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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 \( f > f_c \)) only began to be evident when we examined data records with \( R > 180 \, R_e \).

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 \( f > f_c \), and this fact suggests that some of the observations might involve the \( (n + 1/2) f_c \) 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.

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 \( (n + 1/2) f_c \) 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 \( f \approx n f_c (n = 1,3) \) and a relatively isotropic distribution for the channel with \( f \approx 3f_c/2 \). 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 \( T_e/T_i \gg 1 \). 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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