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CORRELATED WHISTLER AND ELECTRON PLASMA OSCILLATION BURSTS DETECTED ON ISEE-3

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Abstract. The ISEE-3 plasma wave instrument detects associated bursts of electron plasma oscillations and whistler mode waves at an average rate of event one every two days. The plasma wave measurements give the electron number density, and simultaneously measured E and B amplitudes are used to deduce an index of refraction consistent with whistler mode propagation for the measured number density and magnetic field. Burst durations are a few minutes, with some trains of bursts lasting up to an hour. Individual spectral scans (two per second) reveal that the whistler and plasma wave amplitude-time profiles differ within a burst. Peak plasma wave amplitudes are near one mV/m, and the peak whistler mode energy density exceeds that of the plasma oscillations by about a factor 100. The frequency of the whistler mode wave observed in one well diagnosed event agrees with the predictions of the heat flux whistler instability theory. The associated plasma wave instability probably requires a bump-on-tail feature in the heat flux electron component, possibly due to impulsive heating elsewhere on the field-line connecting to ISEE 3.

Introduction

The plasma wave instrument on ISEE-3 has detected a new plasma wave phenomenon in the solar wind. We will show that short bursts of high frequency electron plasma oscillations and low frequency whistler mode waves are often closely associated with one another. The possible interactions between different wave modes, such as between electron plasma oscillations and ion acoustic waves, have been of considerable general interest. However, to our knowledge, an association between plasma and whistler mode waves has received little theoretical attention in the past, and our detection of such an association in the solar wind was unexpected. Our preliminary judgment, based on detailed examination of whistler and plasma oscillation amplitudes at high time resolution, is that these waves may not be associated through direct wave-wave coupling, but rather through sharing a common source of free energy for instability.

The ISEE-3 plasma wave instrument uses continuously active automatic gain control amplifiers to provide rapid high sensitivity measurements of the fluctuating electric fields in the range 10Hz-100kHz (two 16-channel spectral scans per second). Fluctuating magnetic fields in the range 0.3Hz-1kHz are sampled at a lower rate with an 11-channel analyzer. (See Scarf et al., 1978, for details). This instrument regularly records fluctuating electric fields in those frequency channels centered at 10, 17.8, and 31.1 kHz, the range of typical solar wind electron plasma frequencies, as well as in low frequency magnetic field filter channels centered at 17.8, 31.3, and 56.2 Hz, a plausible range for the whistler mode. Activity in these two frequency ranges is usually uncorrelated, and previous studies of electron plasma waves (Gurnett and Anderson, 1977) and whistler waves (Neubauer et al., 1977) have considered them as such. In this paper we concentrate on those occasions when short bursts of activity in the two frequency ranges are associated with one another.

Figure 1 presents eight hours of compressed plasma wave data from November 14, 1978 and February 15, 1979 that contains examples of such bursts. The top sixteen panels on each side show the electric field spectrum, measured in logarithmically-spaced channels between 17.8 Hz and 100 kHz, and presented in terms of telemetry units. (Each panel has an actual range of approximately 90 db). The bottom four panels on each side show the magnetic field spectrum in channels between 17.8 and 100 Hz. Both the peak and average field strengths recorded over a 128-second interval are indicated. A burst of 10 kHz electric field noise near 1345 UT on November 14, 1978 appears to be associated with bursts in the electric and magnetic channels at 17.8, 31.1, and 56.2 Hz. Two similar associated bursts were recorded between 1400 and 1430 on February 15, 1979. In this case, the high frequency electric field noise bursts were found in the 31.1 kHz channel. For the February event, a higher interference level prevented determination of the low frequency electric field presumably associated with the magnetic field fluctuations. Because both electric and magnetic low frequency field measurements were available on November 15, 1978, we will concentrate on this event, which is one of the few for which both components of the low frequency wave were clearly measured.

Associated high frequency electric and low frequency magnetic noise bursts are common in the ISEE 3 data. Inspection of summary data, such as that shown in Figure 1, reveals that 110 similar events were detected between September 7, 1978 and May 22, 1979, for an average of one every two days. Identification of many of these events was confirmed by inspection of higher time-resolution data. This figure may be an underestimate, for several reasons. High frequency bursts could have frequencies between channels, and so be missed. We have occasionally detected, but not surveyed, bursts with frequencies that do not extend above 17 Hz. Furthermore, bursts can be obscured if they are superposed on a generally noisy background, and visual inspection yields no way to determine whether smooth high and low frequency noise events are more than accidentally associated. The pairs of noise bursts that have been identified generally appear to last one or more minutes, with sequences of bursts lasting up to an hour in a few cases. We have found no evident 27-day periodicity or other periodicity in burst occurrence, and no necessary relation between these bursts and the Type III radio bursts also observed on ISEE 3. The pairs of noise bursts are sometimes accompanied by noise in the 562 Hz-5.62 kHz channels ordinarily associated with ion acoustic noise in the solar wind, and sometimes not. We have not yet inspected magnetic field or plasma data with sufficient time resolution to determine if the burst pairs are associated with small scale plasma and magnetic field structures in the solar wind.

In subsequent parts of this paper we will present observations at higher time resolution that show detailed burst-by-burst associations between the high frequency electric and low frequency magnetic field amplitudes. We then use the measured dc magnetic field, the plasma density, and the low frequency electric-to-magnetic field amplitude ratio on November 15, 1978 to identify the wave modes as high frequency electron plasma oscillations and low frequency whistler mode waves. We then compare the whistler and plasma oscillation energy densities at very high time resolution. We close with a discussion of some implications of these observations.

Detailed Associated Between High and Low Frequency Noise Bursts

Figure 2 presents calibrated electric and magnetic field data for 1335-1400 UT on November 14, 1978. The high frequency electric field signals, detected at 5.6, 10, and 17.8 kHz, are consistent with an emission centered near 10 kHz. We deduce an effective bandwidth of 2.5 kHz, using the known frequency response of these channels. The wave magnetic field detector is sampled only 1/32 as often as the electric field detectors, and consequently magnetic data have lower time resolution. Nevertheless, Figure 2 reveals a detailed association between 10 kHz electric field noise bursts and low frequency magnetic field noise enhancements. Strong activity starts in both bands at 1342 and finishes at 1352 UT. Strong bursts of 10 kHz noise rise 3.5 orders of

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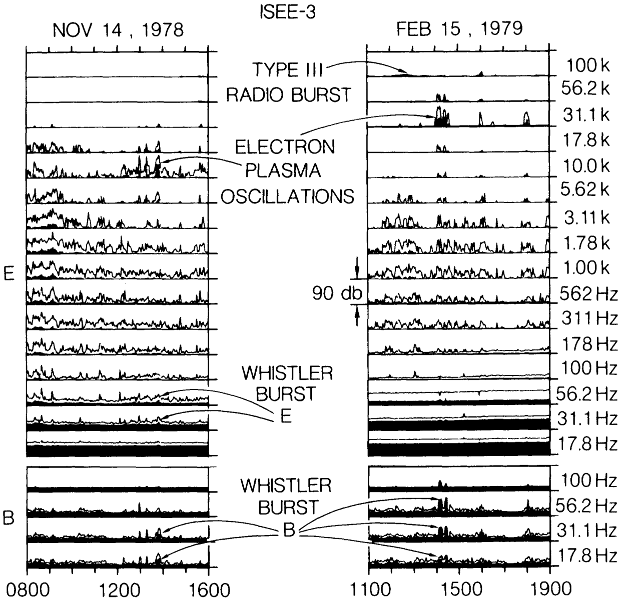

Figure 1. Two associated whistler-plasma oscillation bursts.

Shown here are peak and average electric and magnetic field data for two 8-hour periods containing the events of interest which are identified by arrows. The 16 logarithmically-spaced electric field channel outputs are at the top and the 4 low frequency magnetic channels at the bottom of the right and left inserts. The amplitude scale is logarithmic in telemetry units. The plasma density on November 14, 1978 was sufficiently low that both the electric and magnetic components were above threshold; they will be displayed in greater detail in Figure 3.

magnitude in amplitude above background in about a minute, and it is clear that they occur simultaneously with bursts of low frequency magnetic noise. Three such bursts occur between 1348 and 1352. We will present even higher time resolution data for the last two of these in Figure 4.

Identification of Wave Modes

The ion density reported on the ISEE 3 common data pool tape was about 1.9/cm^3 at 13.49 UT and 13:54 UT on November 14, 1978. Assuming charge neutrality, this would imply a plasma frequency $f_{pe} \simeq$ 12.4 kHz. Within the uncertainty of measurement, we conclude that the waves detected in the 10 (± 15%) kHz channel were electron plasma waves. Similarly, the ion density near 1400 UT on February 15, 1974 was about 13/cm^3, implying a plasma frequency of 32.5 kHz, consistent with the noise burst observed at 31.1 kHz. We believe that the high frequency components of all of the other 110 noise bursts (usually detected at 17.8 or 31.1 kHz, and once at 10 kHz) were also electron plasma waves.

Figure 3 presents simultaneous electric and magnetic fields at f = 31.1 Hz measured on November 14, 1978, one of the few events for which the plasma density-dependent interference in the low frequency electric field channels was weak enough to permit an unambiguous measurement. We can find the magnetic-to-electric field ratio, and thus, the index of refraction, from these data. Individual B/E ratios were determined from individual peak electric and magnetic field amplitude ratios. On this basis we estimate the index of refraction to be about 150. This compares favorably with the theoretical index of refraction n of whistler mode wave propagating parallel to the average magnetic field

$$n = \left[\frac{f_p^2}{f(f_c \cos\theta - f)} \right]^{1/2} \simeq 159$$

where we substituted f = 31 Hz, f_p = 12.4 kHz, and f_c = 241 Hz, based upon an 8.6 γ magnetic field reported in the ISEE 3 common data pool at 1330 UT, and cos θ = 1 (parallel propagation). For n = 150, and the measured solar wind speed at 1349 UT, 505 km/sec, the Doppler effect produces a maximum frequency shift of about 2.5 percent. Within experimental uncertainty, the identification of the low frequency electric and magnetic fields in Figure 3 with the whistler mode seems certain.

Detailed inspection of the low frequency electric field data from some of the other correlated electron plasma wave-whistler bursts, when the solar wind plasma density was higher, reveal less clear traces of low frequency signals that are obscured by interference. However, the measured magnetic-to-electric field ratios have all been consistent with the whistler mode index of refraction in the cases that have been checked, and at this time, we have every reason to believe that the other 109 low frequency magnetic field bursts also represent the whistler mode.

It is of interest to examine the detailed variations in wave activity with the highest available temporal resolution. Since 32 samples of the

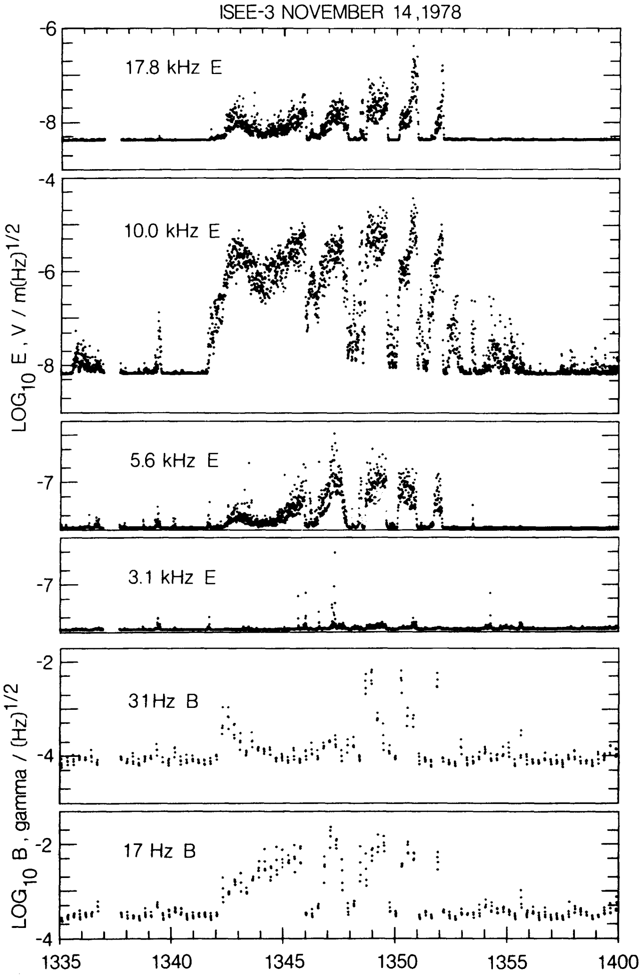

Figure 2. Associated bursts on November 14, 1978.

The top 3 channels, at 5.6, 10, and 17.8 kHz, show the electric field response associated with electron plasma oscillations. The amplitudes at 5.6 kHz and 17.8 kHz, together with the known frequency response in each channel, suggest that the emission amplitude peaks near 10 kHz with a bandwidth of about 2.5 kHz. The lack of activity in the 3.1 kHz channel symbolizes the fact that all channels between 3.1 kHz and 56.2 Hz were inactive. The bottom 2 channels show magnetic field data at 17.8 and 31 Hz, recorded at 1/8 the frequency of electric field data. There is a definite association between the plasma wave and whistler activity, with a detailed association between the 3 shorter bursts observed at 1350 UT.

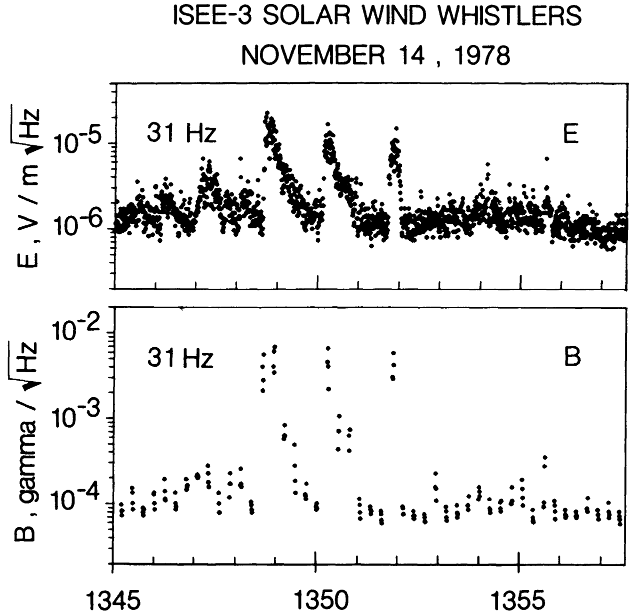

Figure 3. Low frequency electric (E) and magnetic (B) amplitudes.

Shown here are simultaneous electric and magnetic amplitudes measured for the 3 short bursts near 1350 UT in Figure 2. Detailed examination of the individual data points in light of the known time response of the instruments suggests that the B/E ratio is about 150, which is consistent with the whistler mode index of refraction.

whistler mode E-field are obtained for each whistler mode B-field measurement, this requires selection of an event with low levels of E-field interference. The November 14, 1978 event has this characteristic, and Figure 4 compares the electron plasma wave and whistler mode energy densities with 0.5-sec time resolution for the last two large amplitude bursts in Figure 2. The plasma wave electric field energy density was calculated using the measured 10 kHz spectral density and a 2.5 kHz bandwidth estimated previously. The whistler wave magnetic field energy density was estimated using the measured 31.1 Hz electric field amplitudes, an index of refraction of 150, and a bandwidth of 40 Hz. The low frequency sensitivity threshold is shown by horizontal bars; between 1351:00 and 1351:45 UT the whistler amplitudes could have been well below threshold.

We note that the whistler and plasma wave amplitudes do not correlate in detail on the shortest time scale available to us, but that the bursts are associated on a scale of tens of seconds. The peak whistler magnetic field energy density exceeds the peak plasma wave electric field energy density by about a factor 100, although near 1351 UT, the two were comparable for a few seconds. Note that the plasma oscillation electric field energy density drops twice by more than five orders of magnitude in about a second, just before 1351 UT, and just after 1352 UT.

Discussion

The dissimilarity of the whistler and plasma oscillation amplitude profiles on short time scales, and yet their clear association with one another in bursts, suggest that the whistler and plasma waves may not be directly non-linearly coupled, but rather share a common highly variable source of free energy for linear instability. The following discussion is based upon this assumption.

Instabilities driven by solar wind heat fluxes have been discussed by Forslund (1970), Schultz and Eviatar (1972), Gary et al. (1975a,b), Gary and Feldman (1977), and others. Feldman et al. (1976) present what they regard as strong evidence that the whistler mode is active in regulating the solar wind electron heat flux at 1 AU. The whistler instability calculation in Gary and Feldman (1977) is pertinent to the observations presented here. They model the solar wind electron distribution as a sum of core Maxwellian, with T ~ 10's of eV, and a halo Maxwellian with a temperature six times higher, and a density ratio of 19/1. The core and halo drifts parallel to the magnetic field are adjusted so that there is no net electron current, but there is a heat flux away from the sun carried by halo electrons. This distribution is unstable to the growth of whistler mode waves propagating very nearly parallel to the magnetic field along the halo electron drift direction. Doppler-shifted cyclotron resonance with the halo electrons taps the free energy source. They find that the temporal growth rate peaks at 254 times the proton cyclotron frequency, which compares favorably with the measured ratio of 239 for the 31.1 Hz channel on November 14, 1978.

At 1350 UT on November 14, 1978, the solar wind magnetic field was directed southward at an angle of 49° to the ecliptic plane. Therefore, if the whistlers observed were due to an electron heat flux, the heat flux would be most likely of solar wind origin, since unless the field line strongly rotated between ISEE 3 and the earth, it could not connect to electron heat fluxes escaping upstream from the earth's bow shock. The solar wind magnetic field was strongly southward during the February 15, 1979 event as well.

The relative drift between the core and halo electrons in the sample calculation of Gary and Feldman (1977) was the order of the halo electron thermal speed. Therefore, had this drift been chosen somewhat larger, or the halo density somewhat larger, the drifting Maxwellians they chose would have yielded a bump-on-tail instability of electron plasma oscillations. However, at this point, the Maxwellian

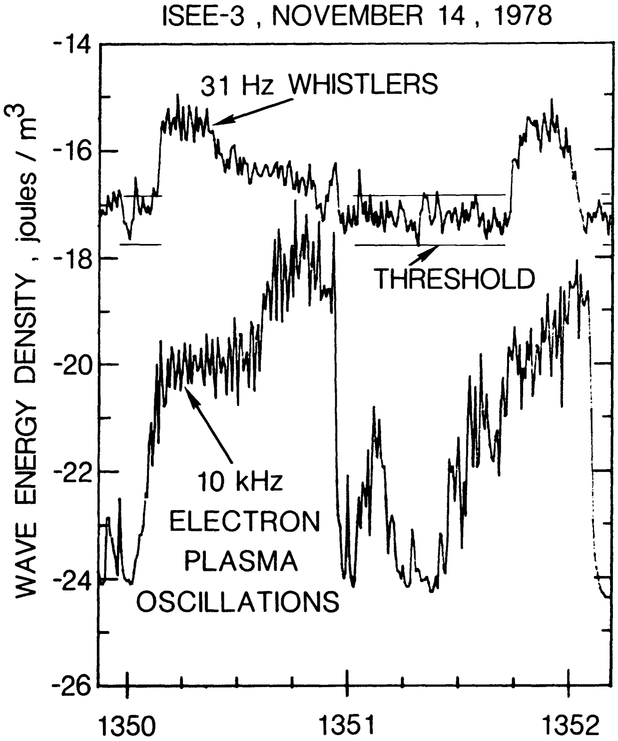

Figure 4. Whistler and plasma wave energy densities.

Here we examine at 1/2-second time resolution the electron plasma oscillation energy density, calculated using a 2.5 kHz bandwidth, and the whistler wave magnetic energy density, using the measured index of refraction and the electric amplitude, assuming a bandwidth of 40 Hz. The threshold set by interference in the 31.1 Hz electric field channel is shown by the horizontal bars. The peak whistler magnetic energy density exceeds the peak plasma wave electric field energy density by about a factor 100. The scale shown gives logarithm to the base 10 of the energy density.

model becomes unrealistic for steady state heat fluxes, which need not have a positive slope in the parallel velocity distribution. However, impulsive heating elsewhere in the field line connecting to ISEE 3 could lead to a short-lived bump on tail by a time-of-flight effect, in which faster electrons arrive at the spacecraft first. The observed burst durations then suggest that the impulsive heat source could be located a few tens to hundreds of earth radii from ISEE 3. Confirmation of this speculative argument awaits more detailed examination of the electron velocity distribution and the small-scale solar wind morphology associated with each event. ISEE 1, 2, 3 comparisons can also help to distinguish between spatial and temporal variations in conditions for generating the instability.

Summary

- The ISEE 3 plasma wave instrument detects associated bursts of electron plasma waves and whistlers, of typical duration of a few minutes, at an average rate of one every two days.

- The whistler and plasma wave amplitude profiles are dissimilar on short time scales within the burst. The peak whistler energy density exceeds the peak plasma wave energy by about a factor 100. The plasma wave amplitude can drop 5 orders of magnitude in a second.

- In the one case examined in detail, the frequency of the whistler observed agreed with the electron heat flux instability predictions of Gary and Feldman (1977).

- The associated electron plasma waves could be a signature of impulsive electron heating on the magnetic field line connecting to ISEE 3.

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