ASSOCIATION OF LOW-FREQUENCY WAVES WITH SUPRATHERMAL IONS IN THE UPSTREAM SOLAR WIND

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Abstract. Observations obtained upstream of the earth’s bow shock with the LASL/MPl plasma instruments and the UCLA magnetometers on ISEE-1 and 2 have revealed a striking relationship between the presence of low-frequency fluctuations in solar wind density and field strength and the different types of distribution functions of upstream ions. Waves are absent when the ions have the beamlike distribution of the “reflected” ions. Large-amplitude waves are present only in conjunction with the “diffuse” ions, which are characterized by flat energy spectra and broad angular distributions. The waves are largely compressive, showing very good correlation between oscillations in magnetic field strength and plasma density.

Introduction

Ions, apparently of bow shock origin, with energies several times the solar wind flow energy are known to exist in the region upstream of the earth’s bow shock, generally on the dawn side (Asbridge et al., 1968). It has been suggested that the low-frequency (0.01 to 0.05 Hz) magnetic waves observed in the same region might be caused by these ions as they stream through the solar wind plasma (Fairfield, 1969; Barnes 1970; Greenstadt et al., 1970). A direct correlation between the presence of the waves and the upstream ions was reported by Scarf et al. (1970). Ions of considerably higher energies have also been observed in the upstream region. Lin et al. (1974) reported the nearly continuous presence of protons with energies above ~30 keV on field lines likely to be connected to the shock. Even at energies above ~100 keV, bursts of protons are quite common in the upstream region (West and Buck, 1976; Sarris et al., 1976). Recently it was shown (Gosling et al., 1978) that there actually are two distinctly different populations of upstream ions at energies between ~1 and ~40 keV, termed “reflected” and “diffuse” ions by these authors. The reflected ions are characterized by their narrow spectral and angular extent, i.e., they form a beam directed outward from the shock along interplanetary field lines. These ions are thus the type originally described by Asbridge et al. (1968). The diffuse ions, on the other hand, are characterized by rather flat energy spectra and broad angular distributions. Peak intensities are much smaller for the diffuse ions, although the total densities are nearly equal.

It is the purpose of this paper to show that the noted difference in upstream ion distributions is associated with a dramatic difference in the occurrence of the upstream low-frequency waves. In addition, the paper will demonstrate the good correlation between magnetic field and plasma density in the wave events. The observations were obtained with the LASL/MPl plasma experiments and the UCLA magnetometers on ISEE-1 and 2. Detailed descriptions of the instruments and data analysis techniques may be found elsewhere (Bame et al., 1978; Paschmann et al., 1978; Russell, 1978).

Observations

Figure 1 shows a 24 minute interval of plasma and magnetic field data obtained on 8 December 1977. The satellites at this time were located near 18 Rg geocentric distance and 300° ecliptic longitude, and moved inward, encountering the bow shock after 21:30 UT. The separation vector in GSE coordinates is (51.3, 349.122) km with ISEE-2 closer to the earth. The magnetic field is shown in terms of its total strength, B. The plasma data are presented in terms of the density, Np, of solar wind electrons and the density Np of suprathermal ions. The electron density, Np, was computed from the two-dimensional distribution function obtained during one spacecraft revolution (~3 seconds). To avoid contamination by photoelectrons, only electrons with energies above approximately 10 eV were included. Since, in addition, spacecraft charging was neglected, absolute electron densities are probably accurate only within a factor of ~1.5.

The suprathermal ion densities, Np, were obtained by integration over only those energy channels clearly above the solar wind protons and alphas. In the case of Figure 1, the integration extended from ~3.1 keV to ~40 keV for ISEE-1 and from ~2.6 keV to ~10 keV for ISEE-2. The difference in limits results from the fact that the two instruments were operated in different energy modes at this time.

Figure 1 shows that initially no suprathermal ions are present and that the solar wind is very quiet, with a density near 10 cm−3 and a bulk speed (not shown) of 300 km sec−1. Near 20:59 UT a low flux of reflected ions first appears, persisting until ~21:02 UT. The (seemingly higher densities seen on ISEE-2 are an artefact caused by the slightly lower integration limit on ISEE-2, as was noted above). The appearance of these reflected ions has no noticeable effect on Np and B. At 21:02 UT there is a sudden onset of magnetic field and plasma density oscillations, coincident with an equally sudden increase in the suprathermal ion density. An inspection of the ion distribution functions (not shown) indicates that these ions are of the diffuse type. The wave amplitudes are very high, with both ΔNp/Ne and ΔB/B being of order one. The transverse oscillations of the field (not shown) are even larger than the compressional. The electron temperature stayed nearly constant at 1.8 × 105 K during the entire interval. Note the good correlation between the Np and B oscillations and between the ISEE-1 and -2 records. The wave periods, in the spacecraft frame, are seen to be slightly less than one minute but with considerable variability. Detailed examination of the magnetic records shows that the phases observed by ISEE-2 are delayed by 0.3–1.0 sec relative to ISEE-1.

A detailed investigation of the waves is beyond the scope of this paper. It requires that the propagation velocity vector, frequency, and polarization be determined in the plasma frame of reference. While the plasma velocity is accurately known, the propagation direction, determined by minimum variance analysis of the magnetic data appears to be highly variable, and sometimes nearly at right angles to the spacecraft separation vector. Thus the observed phase delay between the two satellites cannot be converted to a reliable wave propagation speed by use of a simple model of plane phase fronts sweeping past the spacecraft. The wave polarization is also found to be complicated and variable.

In the data just discussed there was some suggestion that the presence of the waves was correlated with the diffuse ions, but not with the reflected ions. The brief duration and lower densities of the...
Fig. 1. Upstream wave event on 8 December 1977. The top three panels show the field strength B (in gamma), the solar wind electron density Ne (in cm$^{-3}$) and the suprathermal ion densities Np (in cm$^{-3}$) as observed on ISEE-1. The lower three panels show B, Ne and Np from ISEE-2. Spacing for Ne and Np is 3 seconds. B is sampled every 64 msec. The occurrence of reflected and diffuse ion populations are identified by the bars above the Np plot. Spacecraft position was near 18.0 Rs geocentric distance, 306° longitude and 23.5° latitude in ecliptic (GSE) coordinates.

Reflected ions could, however, have accounted for the effect. The next example will demonstrate that the situation is indeed strikingly different for the two types of ions. Figure 2 shows ISEE-2 electron and suprathermal ion densities and magnetic field strength for one hour on 19 November 77. (An ion spectrogram for this interval is shown in Figure 2 of Gosling et al., 1978). At the beginning of the satellite was located at 17.8 Rs and 321° longitude, moving inward and crossing the bow shock near 20:50 UT. The ion density has been computed for energies between ~2.5 and ~10 keV. Figure 2 shows that the low-frequency waves do not appear until about 19:01 UT, although suprathermal ions of substantial density are observed throughout most of this one-hour interval. Before wave onset, however, the ions were of the reflected type, whereas those observed afterwards were of the diffuse type. Note the presence of high-frequency (≥0.5 Hz) fluctuations in field magnitude in conjunction with reflected ions for densities exceeding 0.1 cm$^{-3}$.

Further evidence for the intimate relationship between the presence of the waves and the nature of the ion distribution function is provided by Figure 3, which shows a total of three hours of ISEE-1 plasma and magnetic field data on 8 November 1977. An ion spectrogram for the same data is shown in Figure 1 of Gosling et al. (1978). Near 18:53 UT the bow shock is crossed, as evidenced by the large changes in electron density and average field strength. Note the large time jump between the second and third sections of the figure. The previously noted absence of waves in conjunction with the presence of upstream ions of the reflected type is clearly
Fig. 4. Field strength, electron and suprathermal ion densities from ISEE-1 on 27 November 1977, showing abrupt termination of low-frequency waves and diffuse ions near ~ 90 seconds before bow shock crossing (at 02:49 UT). At the beginning of the interval, the spacecraft was located at ~ 14.6° R_E geocentric distance, 320° longitude and 23.4° latitude in GSE coordinates.

evident during the long interval between ~ 23:10 UT and ~ 23:57 UT, and during two brief bursts near 18:55 and 19:02 UT. In contrast, large amplitude density and magnetic field fluctuations are seen between ~ 20:02 and ~ 20:34 UT, when ions of the diffuse type are present. In addition to these features which already emerged from the previous examples, Figure 3 contains a new feature. Between 19:19 UT and 20:00 UT the upstream ions have a distribution which is broader in energy and angle than normally observed for the reflected ions, but also considerably narrower than is typical for the diffuse ions. (See Figure 1 of Gosling et al., 1978.) During this interval of “intermediate” ion distributions, significant fluctuations in N_E and B are observed, although at much reduced amplitudes. Note that the density of suprathermal ions is nearly the same (~ 0.1 cm^-3) under all conditions. To check whether the orientation of the IMF was controlling the occurrence of these upstream particles and waves we calculated the angle between the IMF and the local expected shock normal. When there were no upstream waves the angle was 58° or greater. When reflected particles were present, it averaged about 50°. When intermediate particles were present, it averaged about 40° and when diffuse particles were present it averaged about 30°.

Finally Figure 4 shows an example of high-resolution data where the low-frequency waves (in N_E and B) and the suprathermal ions (of the diffuse type) terminate just shortly (~ 90 seconds) before the bow shock is crossed (~ 02:49 UT). Again, as in the first example, the field and density fluctuations are in phase. The dominant period is ~ 20 seconds. At the time when the low frequency waves disappear, the high-resolution magnetic field data show an onset of high-frequency waves, extending to the shock. The latter appear to be the whistler waves studied by Fairfield (1974). The noted change in character of the waves is associated with a change in the direction of the magnetic field. When the low frequency waves are present, the field makes an angle of about 30° to the expected shock normal. When the high frequency waves are present and the diffuse ions are absent the field makes an angle of 60° to the shock normal. In both cases the field direction is such that connection to the shock seems inevitable. Therefore it is unlikely that the sudden change in particle and field behavior could have resulted from disconnection from the bow shock.

Discussion

In the previous section we have demonstrated that the presence or absence of low-frequency waves in the upstream solar wind is intimately related to the type of suprathermal ion distribution. Large amplitude waves were exclusively observed in conjunction with the broad distributions of the “diffuse” ion population, and not in conjunction with the narrow-beamed “reflected” population. This fact bears directly on the generation mechanism of the waves. Barnes (1970) has argued that the waves are magnetosonic waves caused by a cyclotron resonance instability of a fast ion beam travelling upstream through the solar wind. He predicts wave amplitudes which are proportional to beam density times its speed (in the solar wind frame). However, our observations indicate that fast ion beams of substantial density can propagate through the solar wind for extended periods (30 minutes and longer) without generating the waves. Quite obviously, if Barnes’ mechanism is correct, there must be additional criteria for instability to occur. Nevertheless, once the waves are generated, they would strongly pitch-angle scatter the ions (Barnes, 1970), resulting in a more isotropic angular distribution. It is therefore tempting to think of the diffuse ions as the end result of the interaction between the original beam and the waves. The fact that the two populations are almost never observed simultaneously, yet have approximately the same densities, fits this picture well. A natural consequence would also be a correlation between wave amplitude and width of the angular distribution, in agreement with the “intermediate” case noted in the discussion of Figure 3. However, although the broad angular distributions of the diffuse ions might be explained this way, their flat energy spectra extending to >40 keV are not. Perhaps the electrostatic fluctuations reported by Scarf et al., (1970) to be associated with the low-frequency wave events can cause the energization. Of course, there might be no causal relationship between the two ion populations at all. Indeed, the correlation of the appearance of diffuse upstream ions and waves with the orientation of the field with respect to the local shock normal suggests that all upstream ions are accelerated at the shock, and that their different properties are associated with the nature of the shock structure at their point of origin. In this context it should also be pointed out that ions similar to the diffuse upstream type are observed downstream of the shock, showing a similar correlation with fluctuations in plasma properties (Asbridge et al., 1978).

No firm conclusion about the origin of the different population of upstream ions and the mechanism for generating the low-frequency waves appears possible at this time. Future work, for example a detailed comparison of the momentum and energy fluxes of the two upstream ion populations, should help to clarify wether a direct causal relationship exists. Studies of the geometry of the intersection of field lines with the bow shock and estimations of conditions at the projected source point of the ions are also necessary.

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