

OBSERVATION OF MIRROR WAVES DOWNSTREAM OF A QUASI-PERPENDICULAR SHOCK

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Abstract. We have performed auto and cross spectral analysis of the electron density and vector magnetic field fluctuations recorded aboard ISEE 1 and 2 in the magnetosheath close to the Earth's bow shock when in quasi-perpendicular configuration. The analysis shows the characteristic signatures of mirror type modes downstream of the undershoot of the shock.

Introduction

Low frequency magnetic field and electron density fluctuations are prominent features of the Earth's magnetosheath [Kaufmann *et al.*, 1970; Fairfield, 1976; Tsurutani *et al.*, 1982; Moustazis *et al.*, 1986]. Measurements reveal a variety of waves at many different frequencies and amplitudes. Downstream of quasi-perpendicular shocks, Rodriguez [1985] found long duration lion roars which provide indirect evidence for the presence of mirror modes; their generation is thought to be due to an electron cyclotron instability caused by the presence of an anisotropic magnetosheath electron temperature [Thorne and Tsurutani, 1981]. Such electron temperature anisotropies have been observed [Tsurutani *et al.*, 1982] in the regions where the mirror waves give a low magnetic field and a high plasma β factor.

Moustazis *et al.* [1986] have reported fluctuations of the electron density and magnetic field with the density and field magnitude in antiphase. This is a characteristic signature of mirror type modes. These observations were made downstream of the bow shock, but their localisation with respect to the shock ramp was difficult because a rotation of the magnetic field and a change of the mean electron density occurred between the time of the observations and the crossing of the shock. Moreover, Alfvén waves were probably superimposed on the compressional mirror modes because the angular distribution of magnetic fluctuations was nearly isotropic.

In this paper we describe ISEE 1 and 2 observations of mirror type modes in the magnetosheath close to the quasi-perpendicular bow shock.

In the last few years our knowledge on the structure of quasi-perpendicular shocks in the solar-terrestrial context has been improved by many theoretical and observational

studies [Leroy *et al.*, 1982; Schopke *et al.*, 1983; Scudder *et al.*, 1986]. Anisotropic ion heating appears to be an important characteristics of quasi-perpendicular shocks and could excite the mirror wave ion instability [Hasegawa, 1975; Tsurutani *et al.*, 1982]. Price *et al.* [1986] provided an analytical and simulation study of the generation of mirror waves. They found that the ion temperature anisotropy can also excite ion-cyclotron waves which compete with non-oscillatory mirror modes; the presence of minor ions in the solar wind may, however, reduce the growth rate of ion-cyclotron waves sufficiently for mirror modes to dominate. Recently Lee *et al.* [1988] have found a large ion temperature anisotropy downstream of a quasi-perpendicular shock in a one-dimensional hybrid simulation. They also found that large amplitude mirror waves develop downstream of shocks with a large Alfvén Mach number. However, a one-dimensional simulation prevents the generation of the Alfvén ion cyclotron mode: this mode is found to be probably dominant within and just behind the shock ramp in the two-dimensional simulation of Winske and Quest [1988].

This letter reports on analysis of magnetic field and electron density measurements obtained by the ISEE 1 and 2 satellites near a quasi-perpendicular crossing of the bow shock. The nature of the low frequency waves present in this part of the magnetosheath is discussed in the light of the correlation between the electron density and magnetic fluctuations, and the magnetic polarization.

The Data

On July 7 1981, on the outbound leg of orbit 567, the ISEE 1 and 2 satellites crossed the bow shock near 17:00 local time at a geocentric distance of 19.8 R_E . The fact that the satellites were outbound when they crossed the shock into the magnetosheath indicates that the bow shock was moving away from the Earth. Integrated electron density measurements from the propagation experiment of the Département de Recherche Spatiale of the Observatoire de Paris [Harvey *et al.*, 1979] were obtained 8 times per second. This experiment measures the phase advance of a radio wave transmitted from ISEE 1 to 2; this is proportional to the mean electron density between the two satellites. Since their separation was only 55 km at the time, the measured average density was very close to a local value. The vector magnetic field was measured 4 times per second by means of UCLA fluxgate magnetometers [Russell, 1978]. The electron density was linearly interpolated to obtain samples coincident with those of the magnetic field.

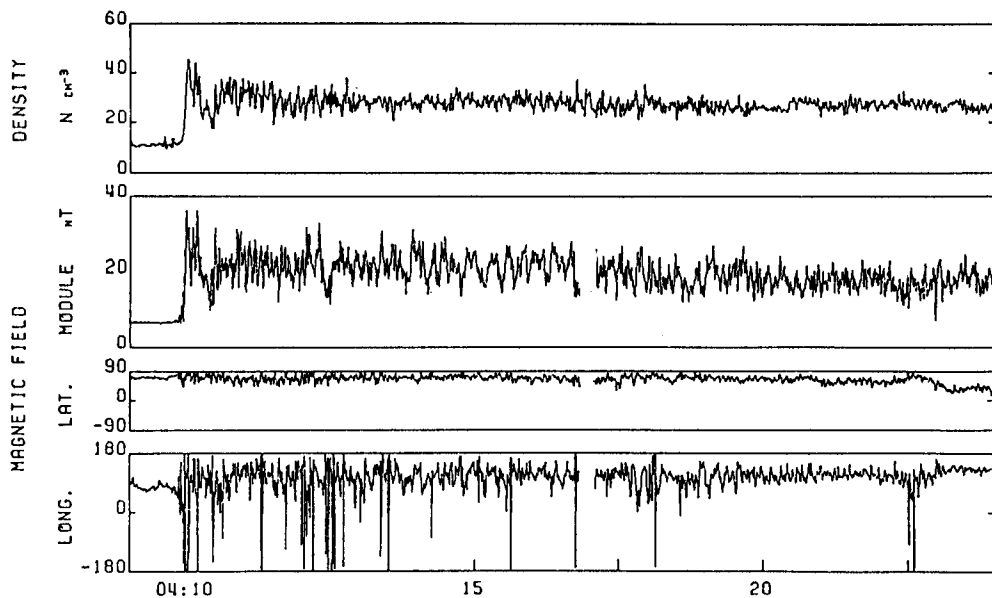


Fig. 1. The top panel shows the electron density measured on day 81/07/07. The lower three panels are the magnetic field magnitude latitude and longitude, in solar ecliptic coordinates, measured aboard ISEE2.

Analysis

The top panel of Figure 1 shows the electron density profile and the lower three panels those of the magnetic field magnitude, latitude and longitude measured aboard ISEE 2 from 04 09 to 04 24 UT, in solar ecliptic coordinates. The satellites crossed the bow shock and entered in the magnetosheath at 04 10 UT. The solar wind electron density was around 11 cm^{-3} and the modulus of the magnetic field was 8 nT ; in the magnetosheath downstream of the shock these two parameters increase respectively to (mean values) of 30 cm^{-3} and 20 nT. A paraboloidal model of the shock [Filbert and Kellogg, 1979] indicates that the angle between the normal and the measured upstream field is about 80° , with an Alfvén Mach number $M_A = 8$ to 9 and an upstream $\beta = 1.5$ to 2.5, these quantities being estimated with use of the NSSDC data [Couzens and King, 1986]. The magnetic field and the density overshoot and undershoot are typical of a supercritical shock, that is, when the ratio of the fast Mach number M_f to the first critical Mach number M_c is greater than 1.0 [Edmiston and Kennel, 1984]. In the present case $M_c \simeq 1.5$ and $M_f = 5$ to 6.

Downstream of the undershoot we observe important fluctuations of the electron density and of the modulus of the magnetic field. Between 04 11 00 and 04 13 00 UT these fluctuations are of large amplitude and the fluctuations of the magnetic field direction are also significant. Further downstream the amplitude of the density fluctuations decreases, but those of the field magnitude remain important. There is a 20 s gap in the magnetic field data around 04 17 UT but the mean direction of the magnetic field is nearly constant, near latitude 90° throughout the interval 04 10 to 04 23 UT.

Spectral analysis of the magnetic field and electron density was performed with a resolution of 0.0156 Hz. Downstream of the undershoot, between 04 10 30 and 04 13 30

UT, there is no significant correlation between the magnetic field and the density fluctuations below the proton gyrofrequency, which was 0.4 Hz. But such an inhomogeneous region requires a study of this correlation on shorter time intervals : this detailed analysis will be given in a subsequent paper and compared to the simulation of Winske and Quest [1988].

Spectral analysis of the period between 04 13 30 and 04 16 30 UT is presented in Figure 2 . The spectrum of the magnetic field component parallel to the average field direction is marked PS(BPAR), that of the perpendicular component is PS(BPER), while the density spectrum is marked PS(D). We note that the parallel component contains much more power than the perpendicular one for the frequencies below the proton gyrofrequency, which is still 0.4 Hz. There is some coherency between the parallel component of the magnetic field and the electron density fluctuations, with a resolved peak of magnitude 0.6 around 0.05 Hz, where the relative phase is close to 180° , as shown in the lower part of Figure 2. During this period the polarization of the waves between 0.03 and 0.06 Hz is nearly linear (axial ratio 2.6) in a direction at $16^\circ \pm 3^\circ$ from the direction of the mean magnetic field B_0 . The wave vector makes an angle $\theta = 74^\circ$ with B_0 .

The results of spectral analysis after the data gap in the magnetic field are shown in Figure 3 for the period 04 17 00 to 04 20 00 UT. The fluctuations of the magnetic field component parallel to the average field direction contain less power than in the earlier period. The spectrum of the electron density shows a peak around 0.07 Hz, much below the proton gyrofrequency which is now 0.35 Hz. There is a clear peak of coherency 0.9 between 0.05 and 0.09 Hz, as shown in the lower left panel of Figure 3. The relative phase between these fluctuations of large coherency is shown on the lower right spectrum of Figure 3 : they are clearly in anti-phase. The polarization of the waves is linear (axial ratio 5.7) at $52^\circ \pm 2^\circ$ from the direction

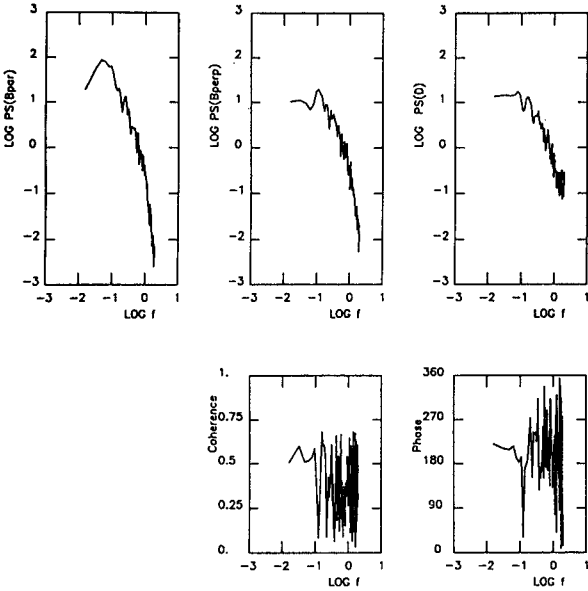


Fig. 2. The results of the spectral analysis of the data between 04 13 30 and 04 16 30 UT. The top three panels show the power spectra of the parallel component PS(BPAR), of the perpendicular component PS(BPERP) of the magnetic field in $\text{nT}^2\text{Hz}^{-1}$ and on the right spectrum of the electron density in $\text{cm}^{-6}\text{Hz}^{-1}$. The lower two panels show the spectral coherency of the fluctuations of the parallel component of the magnetic field, with the magnitude on the left and relative phase on the right.

of the mean magnetic field ($\theta = 38^\circ$). The spectrum of the magnetic field component in the direction of wave polarization (not shown) displays a well resolved peak with a spectral density as large as during the earlier interval from 04 13 30 to 04 16 30.

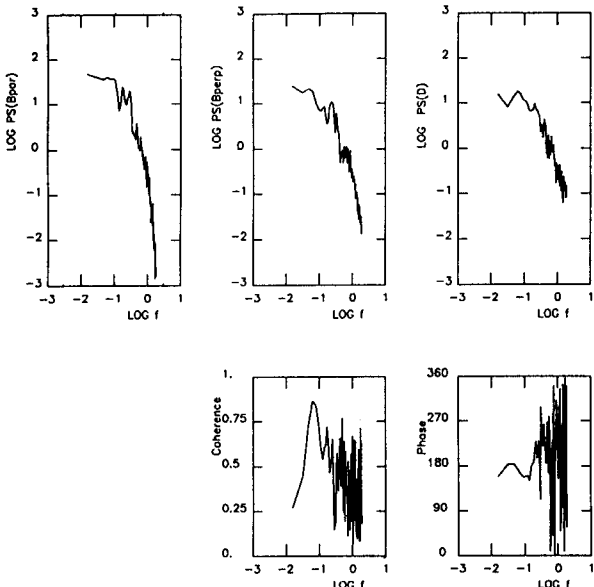


Fig. 3. Spectral analysis between 04 17 20 and 04 20 20 UT, in the format of Fig. 2.

Discussion and Conclusion

We have analysed compressive modes downstream of the undershoot of a quasi-perpendicular shock. In a narrow band frequencies below the proton gyrofrequency the magnetic field fluctuations have a linear polarization and are in anti-phase with the density fluctuations. These results are characteristic of the mirror modes.

Simulations have shown that compressive modes of the non-oscillatory mirror type develop in the region downstream of a quasi-perpendicular shock [Lee *et al.*, 1988]. The β and M_A parameters of the shock crossed at 17 00 LT are within the domain where mirror waves are unstable [see Fig. 3 of Lee *et al.* 1988]. The instability is caused by anisotropic velocity distributions with the perpendicular temperature of the particles species greater than the parallel one [Hasegawa, 1975]. A condition has been deduced by Hasegawa from the relation between the density fluctuations δn and the magnetic fluctuations δB produced by the mirror instability,

$$\frac{\delta n}{n} \simeq \left(1 - \frac{T_{\perp}}{T_{\parallel}}\right) \frac{\delta B}{B_0}$$

where n and B_0 are respectively the mean density and the magnitude of the magnetic field and T_{\perp} and T_{\parallel} the perpendicular and parallel proton temperatures. From our analysis of the fluctuations during the two periods before and after the data gap we estimate

$$\frac{T_{\perp}}{T_{\parallel}} \simeq 1.25.$$

No simultaneous particles observations are available for comparison, but this ratio is close to values deduced in the same manner near the magnetopause when mirror modes are observed [Moustazis *et al.*, 1986; Hubert *et al.*, 1988].

During the two periods of observations of the mirror modes the direction of propagation varies from 74° to 38° from the direction of the mean magnetic field. We note that at these propagation angles for a normalized wave vector $k\rho$ around 1 (where ρ = Larmor radius) the growth rate is nearly the same [Lee *et al.*, 1988].

In conclusion, we suggest that pure mirror modes downstream of the undershoot of a quasi-perpendicular shock have been identified for the first time. Their presence is linked to the anisotropic heating of the protons across the shock which induces the mirror instability. This observation is compatible with numerical simulations which show mirror waves developing downstream of the undershoot of the shock.

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