

# Observations of Magnetohydrodynamic Modes in the Earth's Magnetosheath at 0600 LT

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We have performed an auto and cross spectral analysis of the electron density and magnetic field fluctuations recorded aboard ISEE 1 and 2 in the terrestrial magnetosheath far from the subsolar point. The data were obtained near 0600 local time and roughly equidistant from the magnetopause and the bow shock. The analysis shows the characteristic signatures of mirror type modes when the mean magnetic field is draping the magnetopause, and of Alfvén type wave modes at other times.

## 1 INTRODUCTION

Magnetic field and electron density fluctuations are prominent features of the Earth's magnetosheath [Fairfield, 1976; Moustazis *et al.*, 1986]. The characteristic signature of long period slow mode waves near the nose of the magnetopause was recognized long ago [Kaufmann *et al.*, 1970]. Since then, Kaufmann's results have been confirmed by a number of observations. Crooker *et al.* [1979] observed long period waves in which the electron density and magnetic field strength variations were  $180^\circ$  out of phase; Tsurutani *et al.* [1982] used plasma and field data to identify the instability responsible for generating these modes; Moustazis *et al.* [1986] analyzed the spectrum and coherency of magnetic and electron density fluctuations. All these observations were made near the Sun-Earth line in the region most favorable to the occurrence of such modes. In this paper we report the mirror type modes observed very far from the Sun-Earth line, at 0600 local time (LT).

The scenario for the occurrence of mirror type modes is as follows. Magnetohydrodynamic theory predicts a decrease of the electron density near the magnetopause when the magnetic field is oriented perpendicular to the Sun-Earth line [Lees, 1964; Zwan and Wolf, 1976]. As magnetosheath tubes of force become draped around the nose of the magnetosphere they are squeezed together. The plasma they contain is free to escape along the open field lines, and the resulting field compression and plasma depletion both contribute to the development of anisotropies: the pressure perpendicular to the field direction is greater than the one parallel to it ( $P_\perp > P_\parallel$ ) [Midgley and Davis, 1963; Crooker and Siscoe, 1977]. Under certain conditions, such an anisotropy leads to mirror instability and to the growth of the nonoscillatory drift mirror mode Chandrasekhar [1958]; Hasegawa [1975]; Tsurutani *et al.* [1982]. Density measurements are in good agreement with the MHD model, and thermal anisotropy is found to be a common feature in the dayside magnetosheath Crooker *et al.* [1976 ; 1979]. Nevertheless, no evidence of the  $180^\circ$  phase difference between the electron density and the magnetic field magnitude characteristic

of mirror modes has yet been reported in the magnetosheath far from the Sun-Earth line.

We analyze ISEE observations made on the outbound leg of orbit 22 on December 12, 1977. The magnetopause was crossed  $14.1 R_E$  from the Earth at 0350 UT and the shock was encountered at  $19.5 R_E$  at 1120 UT. The present observations were made from 0722 to 0738 UT, when the satellites were near 0600 LT approximately midway between the magnetopause and the bow shock. The cross-spectral analysis of the magnetic field and electron density fluctuations is performed in three characteristically different intervals. The nature of the MHD waves is discussed in light of the density and field coherency, and the mode polarization.

## 2 DATA

The mean electron density between the ISEE 1 and 2 spacecraft was measured 32 times per second by the Meudon Observatory propagation electron density experiment [Harvey *et al.*, 1978]. This experiment determines the mean electron density by measuring the phase advance of a radio wave transmitted from ISEE-1 and received on ISEE-2. Since the spacecraft separation was only 360 km, the mean density was close to the local value at ISEE-1. The vector magnetic field was measured aboard ISEE-1 16 times per second by means of the UCLA flux gate magnetometer [Russell, 1978]. The electron density was interpolated so as to simulate sampling simultaneous with that of the magnetic field.

Figure 1 shows the projections onto the ecliptic plane of the spacecraft trajectory and, for each of the three periods analyzed, the spacecraft position and the direction of the mean magnetosheath magnetic field (MMF). It also shows, upstream of the shock, the projection of the interplanetary magnetic field direction ( $B_{sw}$ ) during event 2. The MMF data spans the period from 0722:30 to 0738:00 UT when the propagation experiment was active 128 s out of 256 s, as seen in Figure 2. Before and after this interval, the propagation experiment was active 32 s out of 512 s. The lower two panels of Figure 2 show that the MMF rotated significantly at 0731:10 and again at 0733:25 UT, returning approximately to its earlier direction. These times define the three intervals we have studied; they are listed in Table 1. The data were acquired at a geocentric distance of  $17.2 R_E$ , and  $6.6 R_E$  above the ecliptic plane.

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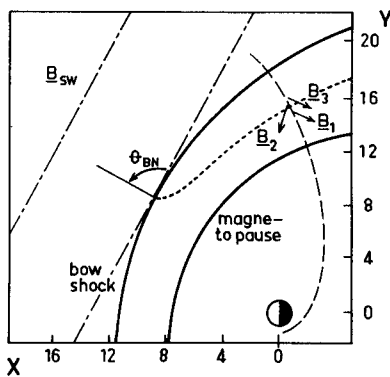


Fig. 1. Projection of the ISEE spacecraft trajectory on the ecliptic plane showing the spacecraft position relative to the magnetopause, the bow shock and also indicating the magnetosheath magnetic field direction onto the ecliptic plane during the three events analyzed on day Dec. 12, 1977. The dotted line in the magnetosheath is the streamline passing through the satellites. The interplanetary magnetic field is represented by the dashed-dotted line, and  $\theta_{BN}$  is the angle between the IMF and the normal to shock at the connecting point of the streamline. Distances along the X and Y axes are measured in Earth radii.

The MMF direction is a consequence of the direction of the interplanetary magnetic field (IMF); the latter was measured with a time resolution of 15.36 s by the IMP 8 spacecraft. The transit time from IMP 8 to ISEE is estimated to be about 400 s, so that during intervals 1 and 3 the corresponding IMF had a  $\sim 40^\circ$  latitude and a longitude of  $\sim 110^\circ$ . During interval 2 the latitude was  $\sim 10^\circ$  and the longitude  $\sim 60^\circ$ , as indicated in Figure 1. The dotted line in the magnetosheath represents the streamline during interval 2 passing through the satellites ISEE 1-2 and connected to the relevant part of the shock [Luhman *et al.*, 1986], where the shock normal is drawn. The angle  $\theta_{BN}$  clearly shows that the magnetosheath streamline passing through the ISEE spacecraft originated from a part of the shock with quasi-perpendicular geometry during interval 2. Similar considerations show the streamlines in intervals 1

and 3 also to be connected to quasi-perpendicular parts of the bow shock.

During periods 1 and 3 the latitude and longitude of the MMF were, respectively,  $\sim 70^\circ$  and  $\sim 130^\circ$ . This is approximately parallel to the Fairfield [1976] model of the magnetopause surface, and thus the MMF is draping it [Zwan and Wolf, 1976]. In period 2 the MMF is inclined to the magnetopause surface close to the ecliptic plane; it is not draping the magnetopause.

### 3 ANALYSIS

Figure 2 shows the electron density and the MMF magnitude latitude and longitude in solar ecliptic coordinates. During periods 1 and 3 the mean electron density was about  $30 \text{ cm}^{-3}$ , and the magnetic field and density fluctuations are large. We will now investigate their correlation.

Spectral analysis of the magnetic field and electron density was performed using a fast Fourier transform algorithm with a spectral resolution of 0.0624 Hz and an estimated error of 27%. The results obtained are similar for the two intervals 1 and 3, where we have density measurements; they are shown in Figure 3 for period 3. The spectra of the MMF components perpendicular and parallel to the average field direction are indicated by PS(BPERP) and PS(BPAR) respectively, while the density spectrum is marked PS(D). The perpendicular component contains less power than the parallel one. The spectrum of the parallel component shows a peak around 0.12 Hz, and is very similar to the spectra obtained by Moustazis *et al.* [1986] close to the magnetopause near the subsolar point. The lower left panel of Figure 3 shows the spectral mutual coherency [Jenkins and Watts, 1968] between the parallel component of the MMF and the density. There is a significant peak of 0.90 around 0.12 Hz; the mean proton gyrofrequency is 0.4 Hz. The spectrum of the relative phase of these two variables is shown in the lower right panel of Figure 3. They are clearly in antiphase near 0.12 Hz, where the coherency is greatest.

The polarization of the waves was studied using the technique developed by Sonnerup and Cahill [1967] and used by Moustazis *et al.* [1986]. Around the peak of mutual co-

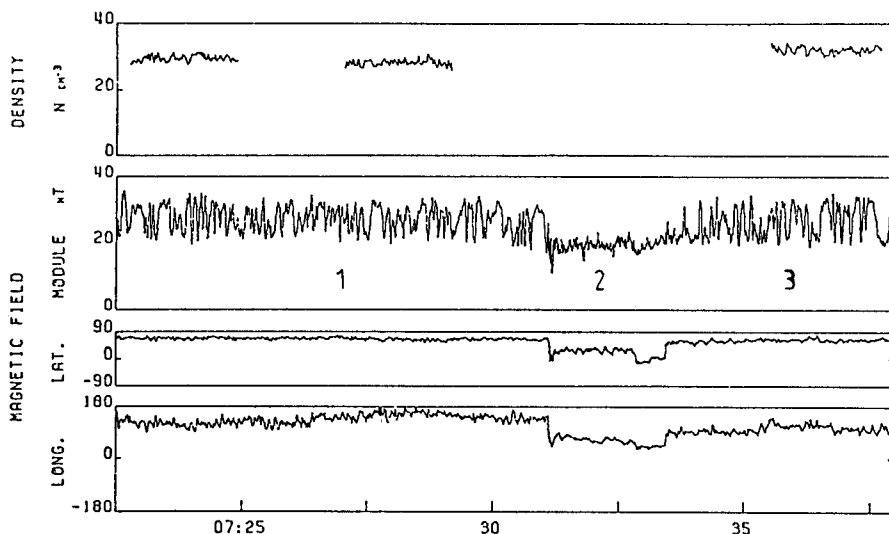


Fig. 2. The top panel shows the electron density. The lower three panels are the magnetic field, magnitude latitude, and magnetic longitude in solar ecliptic coordinates. The three intervals analyzed are noted 1, 2 and 3 in the panel showing the magnetic field magnitudes.

TABLE 1. The three periods analysed in this paper.

Period	Duration		Analyzed	
	From	To	From	To
1	0722:30	0731:10		
2	0731:10	0733:25	0731:10	0733:25
3	0733:25	0738:00	0735:33	0737:41

herency near 0.12 Hz the wave polarization is linear, with the magnetic fluctuations approximately parallel to the mean magnetic field and to the magnetopause surface. Because of the almost purely compressive nature of the magnetic fluctuations, little can be inferred about their direction of propagation from normal minimum variance analysis. As the average magnetic field, its fluctuations and the wave direction  $\mathbf{k}$  are coplanar, the wave normal is parallel to the magnetopause and nearly parallel to the ecliptic plane.

The electron and proton temperatures were measured, with large uncertainties, by the ISEE-1 and ISEE-2 fast plasma experiment [Bame *et al.*, 1978] the proton temperature was greater than the electron temperature,  $T_p > T_e$  [N. Sckopke, private communication]. The anticorrelation between the magnetic field intensity and the plasma density, and the large variations in the magnetic field, indicates that plasma parameters depending on the ratio of these two quantities vary greatly. This is the case of the plasma

$\beta = 8\pi Nk(T_e + T_b)/B^2$ , which is typically 3-4 in the high magnetic field regions but increases to values  $>10$  in the low field regions.

Interval 1 ends at 0731:10 UT when the magnetic field rotates and becomes inclined to the magnetopause surface and nearly parallel to the ecliptic plane. Unfortunately, during interval 2 the propagation experiment data are not good enough to yield the electron density. The spectrum of the magnetic fluctuations during the 135 s duration of interval 2 is shown in Figure 4. At low frequencies there is much more power in the component perpendicular to the average field direction than in the parallel component. The spectrum of the parallel component decreases regularly and is very similar to those obtained by Moustazis *et al.* [1986] in the center of the magnetosheath close to the Sun-Earth line.

During interval 2 the magnetic fluctuations are linearly polarized and inclined at an angle of  $100^\circ$  to the average MMF direction. The magnetic fluctuations are in the same direction as during intervals 1 and 3, parallel to the magnetopause surface. It is interesting to speculate as to whether this could be a general property of the magnetic fluctuations near of the magnetopause whatever the direction of the MMF with respect to the magnetopause surface.

4 DISCUSSION

We have analysed for the first time the density and field fluctuations associated with the MHD modes in the Earth's magnetosheath near 0600 LT and midway between the mag-

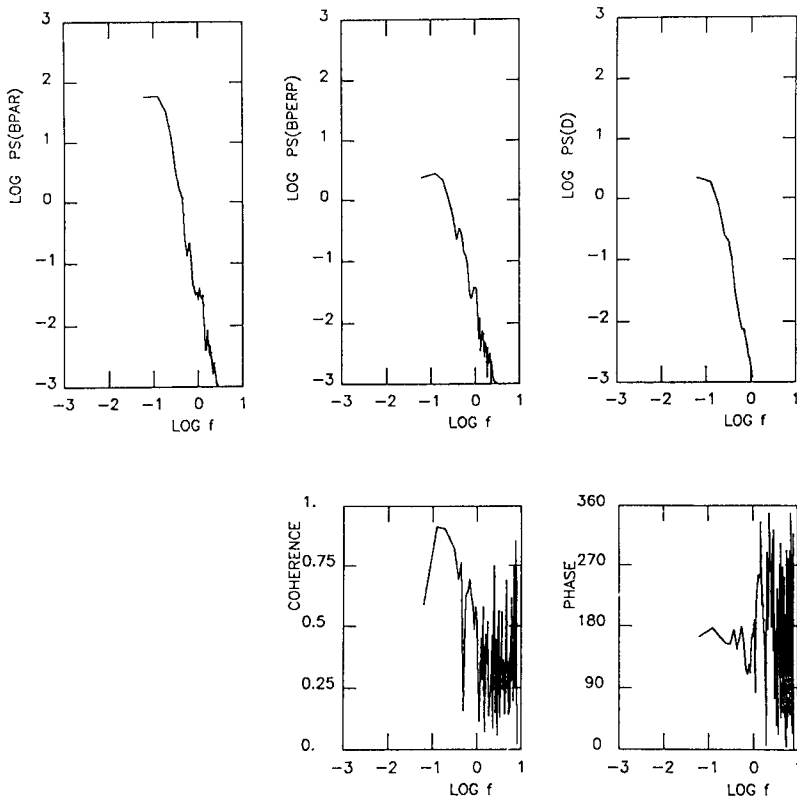


Fig. 3. The results of the spectral analysis of the data between 0735:33 and 0737:41 UT. The top three panels show the power spectra of the parallel component PS(BPAR), of the perpendicular component PS(BPERP), of the magnetic field in  $nT^{-2} Hz^{-1}$ , and on the right the spectrum of the electron density. The lower two panels show the spectral coherence of the fluctuations of the parallel component of the magnetic field, with magnitude on the left and relative phase on the right.

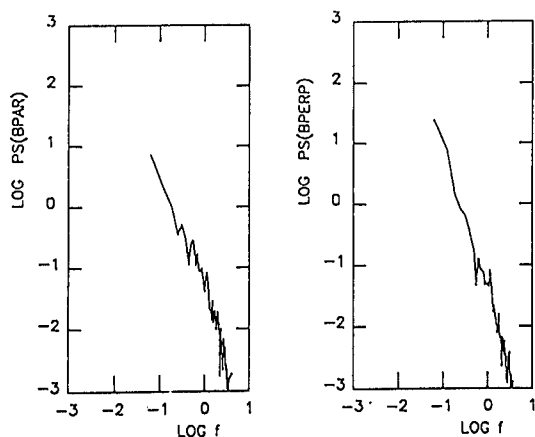


Fig. 4. The results of the spectral analysis of the magnetic field data between 0731:10 and 0733:18; on the left is the spectrum of the parallel component, and on the right is the perpendicular component.

netopause and the bow shock. The type of mode observed correlates with the direction of the magnetosheath magnetic field. When it drapes the magnetopause the modes are compressive, and we observe a significant coherency between the parallel component of the magnetic field and the electron density at frequencies below the proton gyrofrequency. The fluctuations are in antiphase. When the magnetic field is not draping the magnetopause, we observe magnetic oscillations which have the properties of the Alfvén mode.

When the magnetic field drapes the magnetopause the low-frequency waves have the correlation properties of MHD slow modes which are linearly polarized and propagating nearly perpendicularly to the direction of the mean magnetic field. But it seems unlikely that they are indeed such an MHD phenomenon. Such waves in a high- $\beta$  plasma with  $T_e < T_p$  are strongly damped [Barnes, 1966]. The occurrence of compressive modes of the nonoscillatory mirror type could be predicted in regions of the magnetosheath surrounding the magnetopause as the plasma is expected to be very anisotropic. The instability giving rise to these modes is caused by anisotropic velocity distributions with the perpendicular temperature of the particle species greater than the parallel one [Hasegawa, 1975]. A condition has been deduced by Hasegawa [1969] from the phase relation between the density fluctuations  $\delta n$  and the magnetic fluctuations  $\delta B$  produced by the mirror instability. It is

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

where  $n$  and  $B_0$  are the mean density and the magnitude of the magnetic field and  $T_{\perp}$  and  $T_{\parallel}$  are, respectively, the perpendicular and parallel temperatures of the protons. From our analysis of the fluctuations during period 3, we estimate

$$\frac{T_{\perp}}{T_{\parallel}} \cong 1.3$$

This ratio cannot be compared with simultaneous direct particle observations, but is close to values reported in this region of the magnetosheath by Crooker *et al.* [1979]. The growth time of the mirror instability is observed at the beginning of the interval 3. It is about 40 s and is of the order of the value predicted in the magnetosheath [Price *et al.*, 1986].

The mode that we observe in interval 2 is different from that in intervals 1 and 3. While the waves have the signature of Alfvén modes, their identification remains uncertain. Alfvén waves can be produced in situ by the firehose instability, for example, which requires  $T_{\parallel} > T_{\perp}$  [Hasegawa, 1975]. This pressure anisotropy was observed far from the stagnation streamline at 0500 LT by Crooker *et al.*, [1979].

In summary, these results suggest that the observations of mirror modes at 0600 LT, far from the stagnation streamline, in the magnetopause have been made for the first time. Their presence is linked to the draping of the magnetopause by the magnetic field. When the field lines are not draping the magnetopause we observe modes with properties not inconsistent with Alfvén waves. These results are coherent with the spatial distribution of magnetic field fluctuations in the dayside magnetosheath [Luhman *et al.*, 1986]. During all three intervals of observation the streamline passing through the satellites was connected to a quasi-perpendicular shock source which is not an important contributor to the compressible fluctuations. In such cases the background of fluctuations consists of Alfvén waves. When the magnetic field drapes the magnetopause, an anisotropic pressure appears in its environment and produces in situ mirror modes.

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