GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 14, PAGES 2159-2162, JULY 15, 1999

Mirror mode structures observed in the dawn-side magnetosheath by Equator-S

E. A. Lucek,[1] M. W. Dunlop,[1] A. Balogh,[1] P. Cargill,[1] W. Baumjohann,[2]
E. Georgescu,[2,3] G. Haerendel,[2] and K. -H. Fornacon[4]

Abstract. The Equator-S satellite was ideally positioned to make magnetic field observations in the dawn-side magnetosheath, relatively close to the magnetopause. The magnetosheath data were particularly rich in compressional signatures, consistent with mirror mode structures, which occurred during ~30% of orbits crossing into the magnetosheath. In most, although not all cases, strongly compressive signatures extended up to the magnetopause boundary, with no increase in the underlying magnetic field magnitude on the time scale of ten to thirty minutes. The proximity and character of mirror-like fluctuations near the magnetopause suggest that in the dawn-side magnetosheath the plasma depletion layer (PDL) is of narrower extent than is generally observed closer to the subsolar point, or is absent.

Introduction

Equator-S, launched in December 1997, crossed the magnetopause during at least 31 orbits [*Dunlop et al.*, submitted to J. Geophys. Res. Brief Reports, 1999, hereafter referred to as paper 1] and made a number of extended observations of the dawn-side magnetosheath between 1040 and 0600 LT. The orbit, with an apogee of 11.5 R_E, is such that on several occasions the satellite was located in the magnetosheath, relatively close to the magnetopause, for many hours. The spacecraft was therefore well positioned to make measurements near the magnetopause. The present study focuses on compressive wave signatures, but in the absence of plasma data, magnetic field data alone have been used to identify waves in this region of the magnetosheath.

Two types of low frequency waves (f < proton gyrofrequency) which occur in the magnetosheath are electromagnetic ion cyclotron (EMIC) waves, and mirror structures. Both are generated by temperature anisotropy instabilities. The EMIC instability, which generates transverse, left-hand polarised waves, dominates over the mirror instability under conditions of low plasma β [*Price et al.*, 1986; *Gary et al.*, 1993]. These conditions are typically satisfied within a PDL, and EMIC wave occurrence is found to be limited to this region [*Hubert et al.*, 1989; *Anderson and Fuselier*, 1993; *Anderson et al.*, 1994].

[1]The Blackett Laboratory, Imperial College, London, U.K.
[2]Max-Planck-Institute für extraterrestrische Physik, Garching, Germany
[3]Institute of Space Sciences, Bucharest, Romania
[4]Institut für Geophysik und Meteorologie, Technische Universität Braunschweig, Braunschweig, Germany

Paper number 1999GL900490.
0094-8276/99/1999GL900490$05.00

Mirror structures are non-propagating and predominately compressive in nature, [*Tsurutani et al.*, 1982]. The mirror instability is dominant within regions of high plasma β (>5). These conditions are generally met throughout the magnetosheath (outside of any PDL). In magnetic field data mirror structures are characterised by large amplitude variations in the field magnitude within a well defined low frequency envelope. They are typically linearly polarised and have a maximum variance direction which is closely aligned with the mean field [*Erdös and Balogh*, 1996].

This study is based on a survey of spin averaged magnetic field data (0.67 vectors/s) recorded within the magnetosheath. In those orbits which show strong compressional signatures in the magnetosheath, consistent with mirror structures, these signatures in most, although not all cases extend, undamped, up to the magnetopause. Previous observations of the magnetic field signature of the PDL [e.g. *Anderson and Fuselier*, 1993; *Anderson et al.*, 1994; *Phan et al.*, 1994] show that it is characterised by a ramp in magnetic field magnitude over a time scales of the order of ten to thirty minutes, together with the occurrence of EMIC waves. This study draws predominantly on the presence of mirror structures close to the magnetopause, and the absence of a rise in |B| on times scales of ten to thirty of minutes, to suggest that the PDL is narrow (of the order of a few minutes) or absent during the majority, although not all, of these orbits. In the absence of plasma data to confirm the pressure signature of mirror structures, the magnetic field criteria used to identify intervals of mirror activity are described. Some very long intervals occur, allowing an examination of the evolution of the signatures. One typical example is presented. The occurrence is then discussed with relation to the structure of the dawn-side magnetosheath.

Magnetic field observations

A typical example of a long interval of mirror-like activity is shown in Figure 1. The data are from 20 Dec 1997. The panels show field latitude and longitude angles (θ and ϕ) in GSE co-ordinates, magnetic field magnitude |B|, the angle between the maximum variance direction calculated by variance analysis [*Sonnerup and Cahill*, 1967] of locally detrended intervals of 60 data points and average field directions θ_{eB} and $\Delta|B|/|B|$. In GSE co-ordinates X is directed towards the Sun, Z is perpendicular to the ecliptic plane and Y completes the right-handed set; ϕ is positive duskwards and positive θ indicates that the field has a northward component.

The orbit contains a single, well defined magnetopause crossing at 0853 UT [Table 1] which can be seen as a sharp deviation of the field from the steady magnetospheric direction and a drop in field magnitude. The magnetosheath field is southward and ϕ is close to 50° until ~0920 UT when the

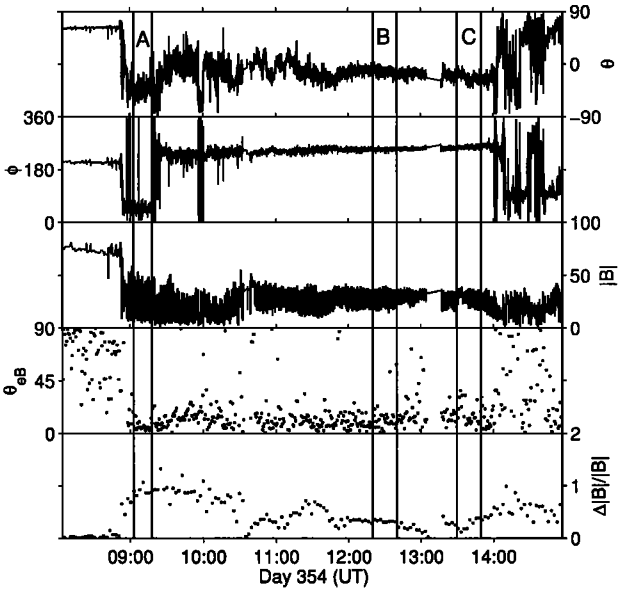

Figure 1. Magnetic field data from 20 Dec 1997. The panels show: field latitude θ, longitude ϕ and magnitude $|B|$, the angle between the maximum variance and average magnetic field directions, θ_{eB}, and $\Delta|B|/|B|$.

field rotates by 180° to about 230°. Both orientations are consistent with draping around the magnetopause as calculated using boundary normal analysis [paper 1], which is consistent with the satellite remaining relatively close to the magnetopause. The field rotation at ~0920 UT and the brief interval between 0956 and 1000 UT are interpreted as sector boundaries, and are consistent with Wind observations of the IMF ~220 R_E upstream of the Earth, approximately 1 hour earlier. There is no apparent change in the character of the mirror structures around the sector boundary, despite the change in shear conditions at the magnetopause which it implies.

Compressional signatures occur within a few minutes of the magnetopause crossing, and continue until ~1400 UT. There is no ramp in field magnitude up to the magnetopause boundary. The angle θ_{eB} remains close to zero throughout but the appearance of the mirror structures shows abrupt changes, for example at ~1140 UT, suggesting that the spacecraft is sampling waves in regions with different local plasma conditions. Three key intervals are presented in panels A, B and C of Figure 2. Close to the magnetopause (A) the mirror waves appear as peaks superimposed on a low field magnitude region and $\Delta|B|/|B|$ is large (>1). Just before 1030 UT the signature changes to a sequence of dips in a high field region during which $\Delta|B|/|B|$ is smaller. Panel B, taken from later in the interval when the field angles are stable, is given as an example of mirror signatures which appear as dips in a high field region. Panel C shows mirror waves containing several intervals with different characteristics. There are sharp shifts in the upper and lower field magnitude values just before 1332 00 and at ~1334 30 UT, and later in the interval the waves become more sinusoidal in shape. It is clear from the figure that the amplitude of the waves varies significantly, and $\Delta|B|/|B|$ varies between about 1 and 0.25 as time elapses after the magnetopause crossing.

The three traces in Figure 3 show the power spectra of the field magnitude during each of the intervals shown in Figure 2. Traces A and B show almost constant power as a function of frequency up to a frequency in the spacecraft frame of ~5×10^{-2} Hz, where a shoulder occurs in the power spectra. Power then decreases with increasing frequency and comparison with high resolution data shows that there

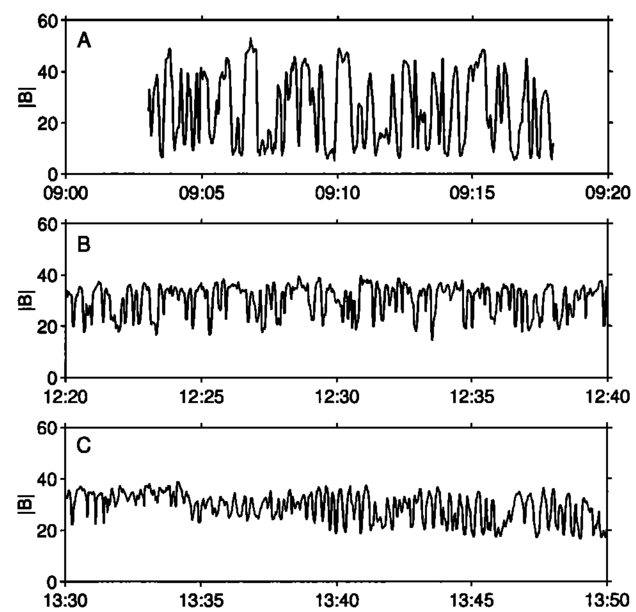

Figure 2. A, B and C show the field magnitude recorded during three intervals from 20 Dec 1997. They illustrate three forms of mirror structure: peaks, dips and a near sinusoidal waveform.

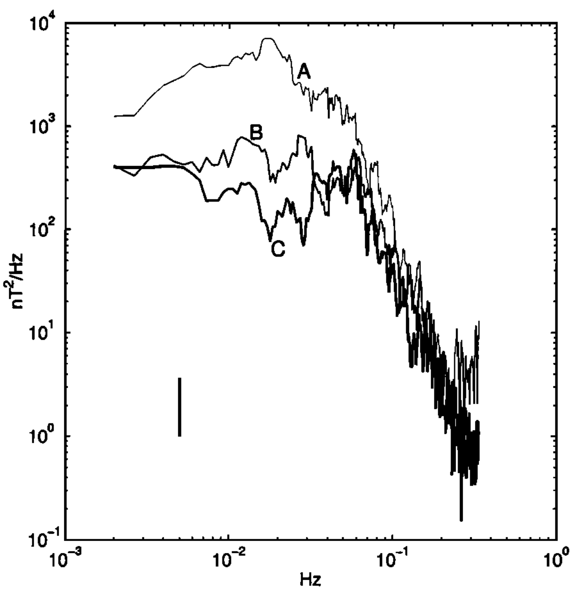

Figure 3. Traces labelled A, B and C show the power spectra calculated for the data in the corresponding intervals in Figure 2. The 90% confidence limit is shown in the bottom left hand corner.

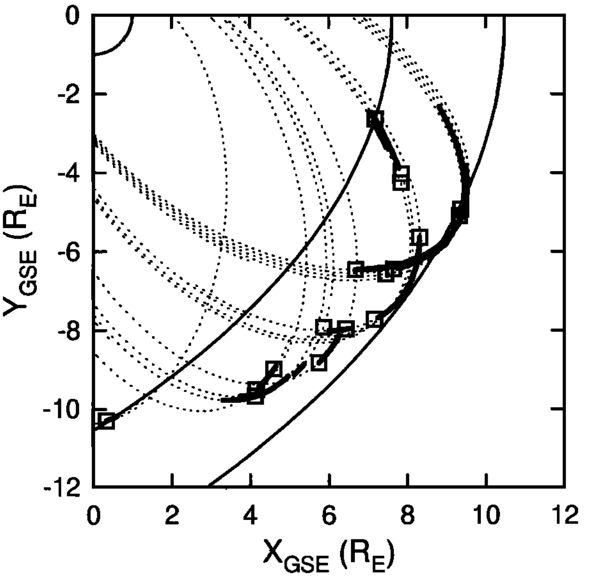

Figure 4. An overview of the occurrence of mirror waves showing Equator-S orbits projected into the GSE x-y plane (dotted lines), magnetopause crossings (squares) and intervals of mirror mode occurrence (heavy lines). The two curves indicate model magnetopause locations for two values for P_{ram}.

is very little power on smaller scales. There is no significant difference in the shape of the power spectra calculated when the mirror waves appear as peaks or when they appear as troughs. Trace C shows that the more sinusoidal wave form is manifested in the power spectrum as a broad peak at a frequency in the spacecraft frame of ~5-6x10^{-2} Hz.

Occurrence

Figure 4 summarises the occurrence of mirror waves, identified by large amplitude, regular fluctuations in |B|, with a small angle between the maximum variance and average field directions. Dotted lines show each of the orbits during which mirror activity occurred, open squares indicate the associated magnetopause crossings, both projected onto the X,Y_{GSE} plane. Also plotted are two lines representing cuts through the model magnetopause of *Sibeck et al.* [1991] at the Z_{GSE} locations of the innermost crossings. The outer trace corresponds to low solar wind pressure (1.8 nPa) and the inner to high solar wind pressure (9 nPa). The duration of each interval of mirror-like activity within each orbit is indicated by a heavy line on the orbit track. The distinguishing feature of these observations is that most of these orbits show mirror signatures extending up to or very close to the associated magnetopause. In most cases the field magnitude does not increase within ten to thirty minutes of the magnetopause, although there are several instances where there may be a signature on the scale of a few minutes. Both of these characteristics indicate the lack of a developed PDL, although a narrow PDL is not ruled out. This is very different from the results reported by *Anderson and Fuselier*, [1993] who noted that, except under radial IMF conditions, a PDL lasting for about ten to thirty minutes typically separated the mirror structures from the magnetopause.

Table 1 summarises the times of clear mirror-like activity within in each orbit. For each interval the date, universal time and local time of the associated magnetopause crossing are given (taken from Table 1 of paper 1). The ratio between the observed magnetospheric field and the nominal model field from the Tsyganenko 1987 model ($(B/B_m)^2$) indicates the local compression of the magnetosphere at the time of the crossing. The start and end times of major intervals of mirror mode activity are given, together with a brief comment about the character of the interval.

Table 1. Mirror mode occurrence and details of associated magnetopause crossings. See text for a full description.

Date	UT	LT	$(B/B_m)^2$	Mirror waves Start End (UT)	Mirror waves Comments
20/12/97	08 53	09 03	1.96	08 57 - 14 00	Interrupted by sector boundary
21/12/97	08 31	09 19	1.44	08 40 - 14 43	
22/12/97	06 34	09 12	1.96	08 58 - 15 30	Several isolated intervals
					Interrupted by offset change
23/12/97	10 50	10 18	1.00	08 10 - 09 07	Other fluctuations follow
06/01/98	04 36	08 35	2.25	03 53 - 04 34	Follows other fluctuations
					Interrupted by magnetopause crossing
06/01/98	05 52	08 51	1.44	06 06 - 10 15	Follows magnetopause crossing
06/01/98	10 24	09 43	2.00		Isolated magnetic holes follow
08/01/98	08 37	09 58	2.56	09 39 - 10 52	Poor estimation of θ_{eB}
08/01/98	10 52	10 43	5.00		Ends at magnetopause
09/01/98	07 30	10 05	1.98	04 40 - 05 05	Between other fluctuations
24/01/98	21 14	08 02	1.00	22 06 - 23 24	Noisy signatures
30/01/98	14 37	08 25	1.00	09 22 - 12 49	Noisy signatures
01/02/98	05 46	07 14	5.37	05 46 - 08 43	Two isolated intervals
07/02/98	21 25	07 34	1.73	21 30 - 22 37	Clear signature but θ_{eB} variable
05/03/98	21 58	06 07	8.00	21 58 - 22 14	Between low shear magnetopause crossings

The example of an interval of mirror mode activity discussed in the previous section is typical of the mirror waves listed in Table 1, although it is one of the longest. All extended intervals of mirror mode activity show significant and abrupt changes in character and although there is some evidence to suggest that $\Delta|B|/|B|$ is dependent on proximity to the magnetopause, the detailed analysis of this will be described in a future paper. The spectral signature typically has a flat or broadly peaked portion with a shoulder at approximately 3-8x10^{-2} Hz, and decreasing power with increasing frequency. Estimates of $\Delta|B|/|B|$ vary between about 0.25 and >1.

Each major interval of mirror activity almost always contains a number of separate bursts. Many intervals are interrupted by data gaps, some of several hours, but some isolated bursts of mirror structures are identified. In several cases mirror structures occur close to multiple crossings of the magnetopause. The angle between the normal calculated for the nearest magnetopause crossing [paper 1] and the maximum variance direction within mirror-like fluctuations is close to 90° in all cases. This indicates that these fluctuations lie approximately parallel to the magnetopause boundary, although other fluctuations, such as those on 22 Dec 1997, do not show such ordering.

Examination of the elevation angle of the sheath field shows that mirror structures occur under both strongly northward and southward field, and that θ often changes significantly during mirror-like activity. The magnetopause crossings occur under a variety of magnetic shear conditions with one instance of a zero shear crossing (05 Mar 1998), but in most cases mirror activity is still located very close to the boundary. Previous observations in the subsolar magnetosheath show that the PDL tends to be less well developed under conditions of high shear [e.g. *Anderson and Fuselier*, 1993; *Phan et al.*, 1994]. The Equator-S observations in the dawn-side flank suggest that, at least in this subset of passes showing strong mirror signatures, the PDL is rarer, or of far reduced extent, under a variety of shear conditions. It is suggested that this result is related to the locations of the crossings far into the dawn-side region, and its significance lies in the high proportion (~30%) [paper 1] of the full set of orbits which contain mirror-like activity.

There is only one pass in this subset of orbits containing a magnetopause encounter which clearly shows the typical signature of a PDL adjacent to one of the main magnetopause encounters (08 Jan 1998). Analysis of high resolution data indicates that wave signatures consistent with EMIC waves occur during the region of enhanced magnetic field and no compressive fluctuations, but not elsewhere.

Acknowledgments. Analysis of Equator-S data at Imperial College is supported by PPARC. The Equator-S mission was made possible through grant 500C94024 by the German Space Agency, (DARA/DLR).

References

Anderson, B. J., and S. A. Fuselier, Magnetic pulsations from 0.1 to 4.0 Hz and associated plasma properties in the Earth's subsolar magnetosheath and plasma depletion layer, *J. Geophys. Res.*, *98*, 1461-1479, 1993.

Anderson, B. J., S. A. Fuselier, S. P. Gary, and R. E. Denton, Magnetic spectral signatures in the Earth's magnetosheath and plasma depletion layer, *J. Geophys. Res.*, *99*, 5877-5891, 1994.

Erdös, G., and A. Balogh, Statistical properties of mirror mode structures observed by Ulysses in the magnetosheath of Jupiter, *J. Geophys. Res.*, *101*, 1-12, 1996.

Gary, S. P., S. A. Fuselier, and B. J. Anderson, Ion anisotropy instabilities in the magnetosheath, *J. Geophys. Res.*, *98*, 1481-1488, 1993.

Hubert, D., C. C. Harvey, and C. T. Russell, Observations of magnetohydrodynamic modes in the Earth's magnetosheath at 0600 LT, *J. Geophys. Res.*, *94*, 17,305-17,309, 1989.

Phan, T. -D., G. Paschmann, W. Baumjohann, N. Sckopke, and H. Lühr, The magnetosheath region adjacent to the dayside magnetopause: AMTPE/IRM observations, *J. Geophys. Res.*, *99*, 121-141, 1994.

Price, C. P., D. W. Swift, and L. -C. Lee, Numerical simulation of nonoscillatory mirror waves at the Earth's magnetosheath, *J. Geophys. Res.*, *91*, 101-112, 1986.

Sibeck, D. G., R. E. Lopez, and E. C. Roelof, Solar wind control of the magnetopause shape, location and motion, *J. Geophys. Res.*, *96*, 5489-5495, 1991.

Sonnerup, B. U. Ö. and L. J. Cahill Jr., Magnetopause structure and attitude from Explorer 12 observations, *J. Geophys. Res.*, *72*, 171-183, 1967.

Tsurutani, B. T., E. J. Smith, R. R. Anderson, K. W. Ogilvie, J. D. Scudder, D. N. Baker, and S. J. Bame, Lion roars and nonoscillatory drift mirror waves in the magnetosheath, *J. Geophys. Res.*,*87*, 6060-6072, 1982.

A. Balogh, P. Cargill, M. W. Dunlop, and E. A. Lucek, The Blackett Laboratory, Imperial College, London, SW7 2BZ, U.K. (email: e.lucek@ic.ac.uk)

W. Baumjohann, E. Georgescu, and G. Haerendel, Max-Planck-Institute für extraterrestrische Physik, Garching, Germany.

K. -H. Fornacon, Institut für Geophysik und Meteorologie, Technische Universität Braunschweig, Braunschweig, Germany.

(Received January 14, 1999; revised May 25, 1999; accepted June 1, 1999.)