Journal of Atmospheric and Solar-Terrestrial Physics 73 (2011) 1398–1404

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Mirror instability upstream of the termination shock (TS) and in the heliosheath

Bruce T. Tsurutani[a,*], Ezequiel Echer[b], Olga P. Verkhoglyadova[a,c], Gurbax S. Lakhina[d], F.L. Guarnieri[e]

[a] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[b] INPE, Sao Jose dos Campos, SP, Brazil
[c] CSPAR, University of Alabama, Huntsville, AL, USA
[d] Indian Institute of Geomagnetism, Navi Mumbai, India
[e] UNIVAP, Sao Jose dos Campos, SP, Brazil

ARTICLE INFO

Article history:
Received 25 March 2010
Received in revised form
3 June 2010
Accepted 9 June 2010
Available online 22 June 2010

Keywords:
Mirror instability
Pickup ions
Heliosheath
Magnetosheaths

ABSTRACT

We experimentally identify mirror mode (MM) structures in the Voyager 1 heliosheath data for the first time. This is done using the magnetic field data alone. The heliosheath MM structures are found to have the following characteristics: (1) quasiperiodic spacings with a typical scale size of $\sim$57 ρ_p, (2) little or no angular changes across the structures ($\sim3^\circ$ longitude and $\sim3^\circ$ latitude), and (3) a lack of sharp boundaries at the magnetic dip edges. It is demonstrated that the pickup of interstellar neutrals in the upstream region of the termination shock (TS) and quasiperpendicular TS plasma compression are the causes of MM instability during intervals when the IMF is nearly orthogonal to the solar wind flow direction. Concomitant additional injection of pickup ions (PUIs) throughout the heliosheath will lead to further MM amplification. MM structures in planetary magnetosheaths and interplanetary sheaths are discussed for comparative purposes. Multiple sources of free energy are often involved.

1. Introduction

Significant, large-amplitude magnetic field magnitude structures have been detected in the heliosheath by Voyager 1 (Burlaga et al., 2006, 2007, 2008). These structures have been identified by the above authors as "magnetic holes" (MHs). Burlaga et al. (2007) have noted them to be "linear" (Burlaga and Lemaire, 1978; Winterhalter et al., 1994; Zhang et al., 2009) or MHs that have little or no magnetic field angular changes across them.

Structures also called MHs have been detected in interplanetary space much closer to the Sun (Turner et al., 1977; Winterhalter et al., 1995; Neugebauer et al., 2001). It is possible that these interplanetary structures are different from those in the heliosheath, so we will call the latter structures magnetic decreases (MDs: Tsurutani and Ho, 1999; Fränz et al., 2000; Tsurutani et al., 2002a, b, 2009) to avoid confusion.

The above studies have determined that interplanetary MDs have the following properties: (1) they can occur singly, but if multiple events are present, they are not quasiperiodic, (2) the scale size can vary between a few ρ_p to >1000 ρ_p, where ρ_p is the proton gyroradius, (3) although some MDs have small angular changes across them, most ($\sim$70–90%) of them contain significant angular changes, and (4) MDs are typically bounded by sharp edges (Tsurutani and Ho, 1999; Fränz et al., 2000). Fränz et al. (2000) found that 78% of MDs were bound by tangential discontinuities. Farrugia et al. (2001) have examined one MD edge in detail and have concluded that it was a slow shock. (5) MDs are total (plasma+magnetic) pressure balance structures.

Another type of phenomenon that have decreases (and apparent increases) in the ambient magnetic field are mirror mode (MM) structures. These have been identified in the magnetosheath of Earth (Tsurutani et al., 1982, 1984; Lacombe et al., 1992; Anderson and Fuselier, 1993; Lucek et al., 1999a, b, 2001; Dunlop et al., 2002; Tátrallyay and Erdos, 2002, 2005; Horbury et al., 2004, Narita and Glassmeier, 2005; Horbury and Lucek, 2009), the magnetosheath of Jupiter (Tsurutani et al., 1982, 1993; Balogh et al., 1992a, b; Bavassano Cattaneo et al., 1998), in Saturn's magnetosheath (Tsurutani et al., 1982; Violante et al., 1995; Bavassano Cattaneo et al., 1998), in Venus' magnetosheath (Volwerk et al., 2008a, b), and at comets (Russell et al., 1987; Tsurutani et al., 1999). MMs have been detected in interplanetary space (Tsurutani et al., 1992) but only rarely. From the above articles, the properties of MM structures are: (1) they are quasiperiodic (convected) oscillations in $|B_o|$, (2) the scale size of the structures vary from 20 to 50 ρ_p, (3) there are little or no angular changes across the structures, (4) the magnetic dips (or increases) are smoothly varying and do not have sharp edges, (5) tens of these quasiperiodic structures occur sequentially, and (6) MMs are total-pressure balance structures.

MM structures are created by an instability when the condition $\beta_\perp/\beta_\parallel > 1+1/\beta_\perp$ is satisfied (Chandrasekhar et al., 1958; Vedenov

* Corresponding author. Tel.:+1 818 3547559.
E-mail address: bruce.tsurutani@jpl.nasa.gov (B.T. Tsurutani).

1364-6826/$ - see front matter © 2010 Published by Elsevier Ltd.
doi:10.1016/j.jastp.2010.06.007

and Sagdeev, 1958; Shapiro and Shevchenko, 1964; Hasegawa, 1969, 1975; Price et al., 1986; Migliuolo, 1986; Brinca and Tsurutani, 1989; Southwood and Kivelson, 1993; Leubner and Schupfer, 2000; Pokhotelov et al., 2004, 2008). In the above expression, $\beta = 8\pi nkT/B^2$, the ratio of the plasma thermal pressure to the magnetic pressure. The subscripts "$_\perp$" and "$\|$" refer to the components perpendicular and parallel to the ambient magnetic field B_o, respectively. The structures are nonoscillatory (nonpropagating) structures (Hasegawa, 1969) and are convected by the flowing plasma to the first order (Tsurutani et al., 1982; Horbury et al., 2004).

The purpose of this paper is to examine the Voyager 1 heliosheath magnetic field data and to determine if these magnetic features are MM structures or not. Liu et al. (2007) and Genot (2008) have suggested that perpendicular shock compression of upstream plasma can produce mirror instability at the termination shock. The purpose of this paper is to study the detailed features of these structures to experimentally determine if they are indeed mirror mode structures based on previous determined planetary magnetosheath criteria. If they are MM structures, we will explore other sources of free energy for instability in addition to shock compression. In addition a comparison to MM structures in planetary magnetosheaths will be made that will hopefully be useful to the interested reader.

2. Method of analysis

The Voyager magnetometer data were obtained from the Goddard Space Flight Center deep space solar wind data (http://cohoweb.gsfc.nasa.gov). Only 1 h average data were available. There were many tracking gaps present, so computer analysis was not possible. The data were therefore hand-analyzed. The data were present in RTN coordinates. In this system, R points radially away from the sun, T is $\mathbf{\Omega} \times \boldsymbol{R}/|\mathbf{\Omega} \times \boldsymbol{R}|$ where $\mathbf{\Omega}$ is the direction of the sun's north rotation pole and N completes the right-hand system. The values of θ (latitude) and φ (longitude) were calculated. The maximum deviation of these values from the point of the minimum value of the field magnitude to the background field at the edges of the magnetic dip was calculated. These maximum values were then recorded as the deviations $\Delta\theta$ and $\Delta\varphi$ for that cycle/dip. Each cycle was calculated in a similar manner and was tabulated. These results will be presented and discussed later. Partial cycles were not used in this study.

The plasma instrument onboard Voyager 1 had failed and it is not possible to determine the relationship between plasma pressure and magnetic pressure for the magnetic dips. That is unfortunate because this data could have been used to distinguish between different wave modes. For instance, mirror mode structures have magnetic and plasma pressures that are 180° out-of-phase (Hasegawa, 1969; Tsurutani et al., 1982; Price et al., 1986), whereas fast magnetosonic waves or solitary waves predicted by application to the Derivative Nonlinear Schrodinger (DNLS) equation (Buti et al., 1998) have the partial pressures that are in-phase.

To understand the pickup of interstellar ions, we use the plasma velocity measurements of the Voyager 2 spacecraft. The solar wind decreases abruptly close to the termination shock and we use these published values to estimate the pickup energy densities. These values are then applied to the Voyager 1 case. This will be discussed in more detail later in the paper.

The magnetic properties of MMs are well established from not only theory but also by at least tens of observational articles. MDs, which are detected in interplanetary space have considerable different properties. The discriminating features of MMs and MDs have been discussed above. Because these properties are so well established in the literature (with no debate), use of the magnetic field data alone is sufficient to determine whether the heliosheath structures are MMs or MDs.

3. Results

3.1. Heliosheath MM structures or MDs?

Fig. 1 shows Voyager 1 heliosheath data (at ~95 AU) in RTN coordinates. The top panel of the figure shows the high degree of variability of the magnetic field. Of particular interest are the large decreases in the field magnitude B_o (bottom panel). The high spatial-resolution inset shows that the $|B_o|$ varies over a single field MM dip. The decrease is smoothly varying. This is typical of the structures examined.

It is important to examine heliosheath/magnetosheath angular components of the magnetic field to determine if changes across the structures exist (Tsurutani et al., 1982). The bottom panel of Fig. 1 shows the magnetic field in polar coordinate angles: latitude (θ) and longitude (φ).

Fig. 2 gives quantitative results of a detailed examination of the angular changes across the magnetic dips. 96 events from the 2006 Voyager 1 data were studied. It is found that the latitudinal angular changes ($\Delta\theta$) given in the top panel had a median of 2.7° with a mean of 4.4°. The longitudinal angular changes ($\Delta\varphi$) given in the bottom panel had a median of 3.3° and a mean of 5.5°.

Fig. 3 shows the spatial scale sizes of the magnetic dips given in ρ_p. For these calculations a heliosheath convection speed of ~100 km/s and a proton perpendicular kinetic energy of ~1 keV were assumed. The histogram vertical axis is the percent of the total number of events analyzed. It is found that the median size was 57 ρ_p with a mean of 63 ρ_p. Burlaga et al. (2007) reported a scale size of ~80 ρ_p. Because slightly different assumptions were made, and different data intervals analyzed, we conclude that the two results are in reasonably good agreement.

The smooth edges of the heliosheath structures (Fig. 1), the small angular changes across the structures (Fig. 2), and the quasiperiodic nature of the structures (Fig. 3) all indicate that these structures are mirror modes. These three properties are not found in interplanetary MDs.

3.2. Source of "free energy" for heliosheath mirror instability

For the region upstream of the TS, we use the following solar wind parameters: $N = 10^{-3}$ cm^{-3}, $B_o = 5 \times 10^{-2}$ nT, and $T = 10^4$ K (G. Zank, personal comm., 2009). The above values describe the solar wind plasma, neglecting pickup ions. The upstream β is therefore ~0.14. The solar wind speed at Voyager 2 has been observed to decrease by ~20–30% as it approaches the TS (Richardson, 2008; Richardson and Stone, 2008). We assume that these same numbers apply for the Voyager 1 crossing (no plasma data are available). We will use a conservative value of 20% speed decrease. Making a simple assumption of conservation of momentum, this implies a 25% increase in solar wind mass. Therefore $N_{pickup} = 2.5 \times 10^{-4}$ cm^{-3}. If the ions (protons) are assumed to gain ~1 keV in perpendicular kinetic energy by the pickup process, β_{pickup} is ~40. Thus the upstream plasma will be dominated by the pickup ions. The upstream B_o will not be perfectly orthogonal to the solar wind flow, as one might expect from theoretical arguments (see Fig. 1 in Burlaga et al. (2006) for such an example). The presence of convected Alfvén waves (and other phenomena) will ensure deviations from this ideal condition. If we assume that the interplanetary magnetic field varies ~10° away from orthogonal due to long period Alfvénic fluctuations, the

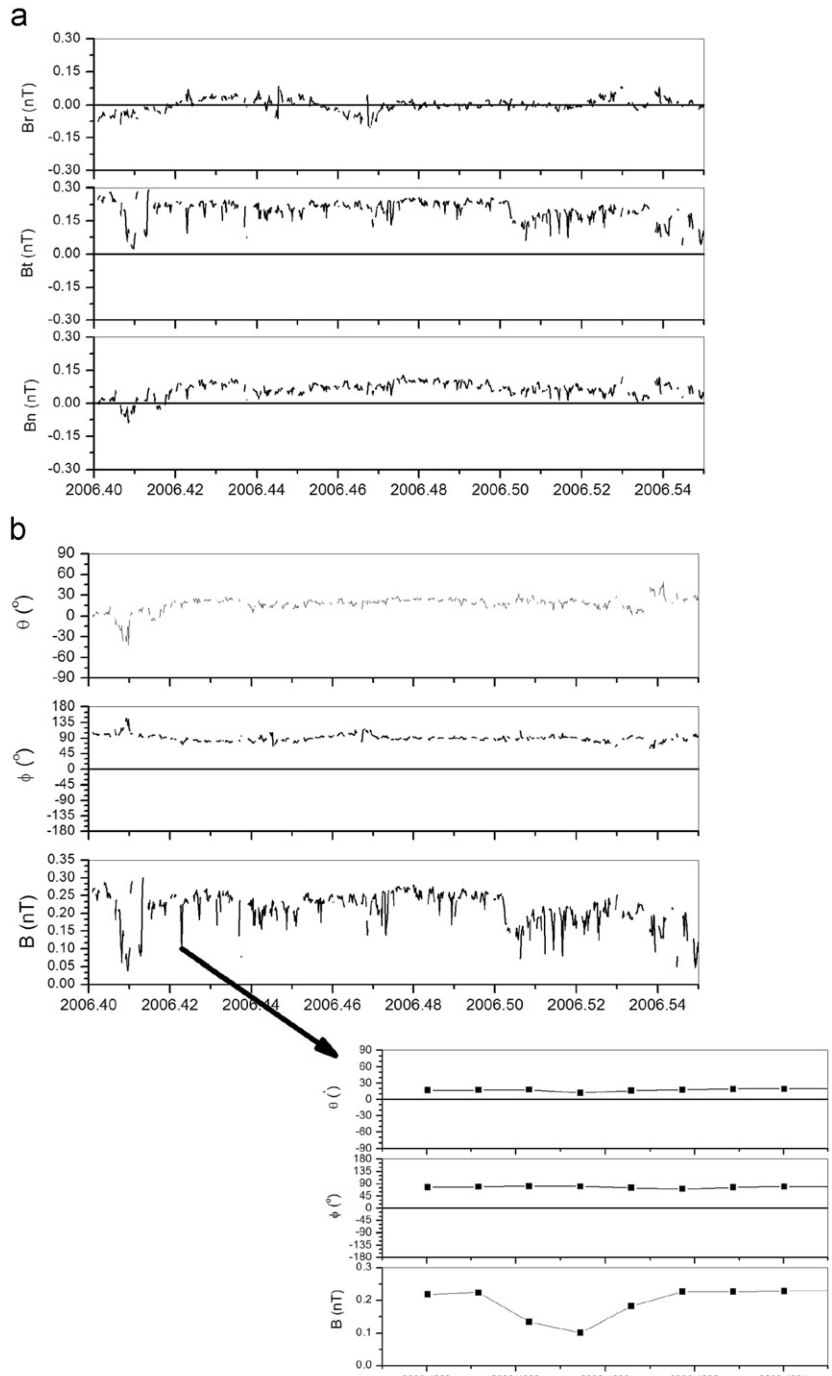

Fig. 1. Voyager 1 heliosheath magnetic fields shown in *R*, *T*, and *N* coordinates (top panel) and in spherical coordinates in the bottom panel. The data were taken during 2006 at ~95 AU from the sun.

ratio of $\beta_\perp/\beta_\parallel$ will have a value of ~9, much larger than the instability criterion of ~1.1. For larger B_o angular variations, this ratio will be lower. In any case, it is apparent that significant mass loading can trigger MM growth upstream of the TS.

If the upstream magnetic field is nearly perpendicular to the solar wind flow, the TS will be almost perpendicular in nature. The upstream MM structures will be convected into the TS and will be compressed further. Since the MM structures are large-scale and oriented along B_o, they will presumably retain the same scale size and relative amplitudes. Additional free energy input for MM instability will be added by ion perpendicular heating from shock compression (Liu et al., 2007; Fahr and Chalov, 2008). Pickup of interstellar ions occurring in the heliosheath will add even more free energy. Continuous free energy put into the system should lead to MM growth to unusually large amplitudes until nonlinear saturation occurs.

4. Summary and conclusions

We have demonstrated that the magnetic structures present in the Voyager 1 heliosheath data are MM structures. This was done using magnetic field data alone. The structures: (1) are quasiperiodic, (2) are smoothly varying with a lack of sharp edges,

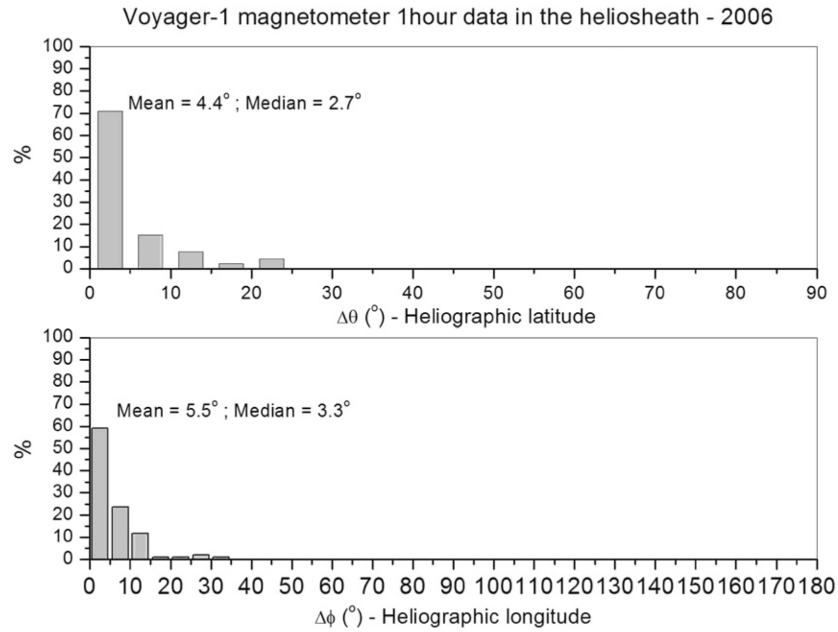

Fig. 2. Histograms of the angular changes (in θ and φ) across the MM dips. The histograms are binned in 5° increments and the vertical scales are given in percentage of total. Ninty-six magnetic dips were selected at random and were used in these statistics.

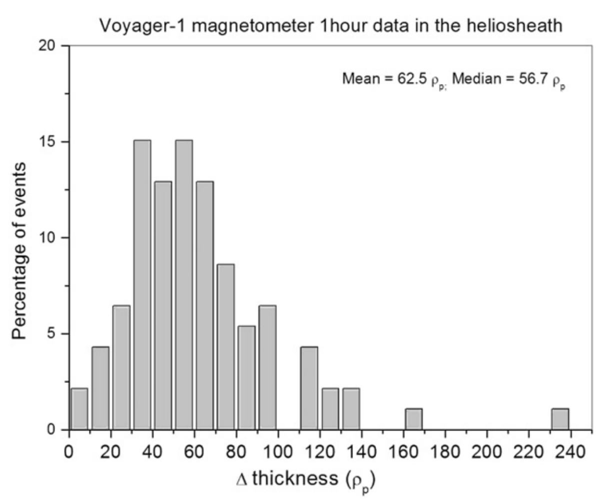

Fig. 3. The distribution of the separation of the MM dips. The size is given in ρ_p.

(3) have scale size of ~57 ρ_p, (4) are a continuous chain of tens of quasiperiodic cycles, and (5) there is little or no change in B_o directionality across the structures. The source of free energy for MM instability is the pickup of interstellar ions in the upstream region when the magnetic field is nearly orthogonal to the solar wind flow. Upstream MMs will be convected into the TS and will become compressed. However being large scale features, their nature (scale size and amplitude) will remain unchanged.

Additional free energy will be added to the system by further anisotropic heating by the (perpendicular) TS compression and by additional interstellar ion pickup within the heliosheath.

It should be noted that recent arguments indicate that the majority of interplanetary MDs are of a different phenomenon and are not generated by the MM instability (Tsurutani et al., 2009). The latter authors have suggested that most MDs studied were caused by either (Alfvén) wave or discontinuity interactions with quasiparallel shocks.

Table 1
Comparison of MM scale size in the magnetosheaths of Earth, Jupiter, and Saturn to that in the heliosheath.

Magnetosheath environment	MM scale, ρ_p	Source
Earth	20	Tsurutani et al. (1982), Lucek et al. (2001), Horbury and Lucek (2009)
Jupiter	20–25	Tsurutani et al. (1982), Erdos and Balogh (1996)
Saturn	40	Tsurutani et al. (1982)
Heliosheath	80	Burlaga et al. (2006)
	57	This paper

4.1. *Comparison of heliosheath mm structures to those in planetary magnetosheaths*

It is useful to compare the heliosheath MM structures to those observed in planetary magnetosheaths. Table 1 shows a comparison of the MM structures scale sizes in the magnetosheaths of Earth, Jupiter, and Saturn to those in the heliosheath. The MM scale size is ~20 ρ_p at Earth, ~20–25 ρ_p at Jupiter, and ~40 ρ_p at Saturn.

It is noted that the MM structures become larger as one progresses from the Earth, to Jupiter, to Saturn, and to the heliosheath. Such variation is not accounted for in present MM instability theory. It should be noted that dominant MM mode linear growths (scale sizes) are currently being debated (Stasiewicz et al., 2003; Pokhotelov et al., 2005; Hau et al., 2005; Klimushkin and Chen, 2006; Hellinger, 2008). However none of the works identify growth of such large scale structures as 57 ρ_p. Thus at present there is no explanation for this part of these observations. Recently Shoji et al. (2009), using a 3-D hybrid code, found that MM coalescence occurs with time, leading to larger scale structures as the MMs are convected deeper into the magnetosheath. The magnetosheaths of Jupiter and Saturn are larger than those at Earth's. Thus one possible explanation of the observations is that the MM structures in outer planetary magnetosheaths have convected for a longer time and thus have coalesced to larger scale sizes. On the other hand, Tátrallyay and Erdos (2005) found that the MMs at Earth did not change scale sizes from the shock to the magnetopause. It will be interesting to determine if the heliosheath MM structures become larger and larger as Voyager 1 approaches the heliopause or if the scale size remains constant.

4.2. Planetary magnetosheath MM free energy sources

Numerous planetary observations indicate that the MM amplitudes are small or nonexistent near the bow shock and are the largest near the magnetopause (Erdos and Balogh, 1996; Bavassano Cattaneo et al., 1998; Lucek et al., 1999a; Tátrallyay and Erdos, 2005; Figs. 13 and 14 in Tsurutani et al., 1982). This is also theoretically expected (Midgley and Davis, 1963; Zwan and Wolf, 1976) because there are two sources for the generation of large $\beta_\perp/\beta_\parallel$ ratios (the free energy for instability) for planetary magnetosheaths: quasiperpendicular shock compression and magnetic field line draping.

Planetary bow shocks are fast reverse shocks with magnetosonic Mach numbers >7. The heating of solar wind ions perpendicular and parallel to the ambient magnetic field as they cross the shock depends on the angle that the field makes relative to the shock surface. If the field is parallel to the shock surface (a perpendicular shock, because the shock normal will be orthogonal to the upstream field direction) the heating will be perpendicular to B_o. If the upstream magnetic field is perpendicular to the shock surface (a parallel shock), the plasma heating will be parallel to the field. Planetary bow shocks have regions where the shock is perpendicular in nature and also regions where they are parallel in nature (Tsurutani and Rodriguez, 1981). It is the quasiperpendicular part of the bow shock that leads to plasma anisotropies that could lead to mirror instability. The quasiparallel portion of the shock will cause plasma heating that will lead to mirror stability.

In the other source of free energy for MM instability, the field line draping mechanism (Midgley and Davis, 1963; Zwan and Wolf, 1976), magnetic field lines that drape over the magnetosphere will both compress the plasma perpendicular to B_o (increasing $T_\perp$) and also squeeze plasma out the ends of the lines of force, effectively reducing $T_\parallel$. This additional free energy for MM growth will be applied throughout the subsolar region of the magnetosheath.

Tátrallyay and Erdos (2005) have statistically examined the location of MM structures in the Earth's magnetosheath. They found that the major location of MM structures were found at the magnetopause and not near the bow shock. They also found symmetry between the dawn and dusk MM concentrations. Tátrallyay and Erdos (2002, 2005) concluded that magnetic draping is the dominant source of instability for the Earth's magnetosheath.

To illustrate the above features, we present Fig. 4, observations of MM structures in the Saturnian magnetosheath. Little or no MM structures are noted just downstream of the fast reverse shock. The MM structures start to grow about 1/3 of the way through the magnetosheath and reach maximum amplitudes near the magnetopause. This is typical of MMs in planetary magnetosheaths.

An interpretation of the Saturnian magnetosheath observations is that the sources for free energy for MM instability are both quasiperpendicular shock compression plus additional magnetic field draping. What is not understood is why MMs are not detected throughout the magnetosheath. There should be some place on the bow shock where the shock is perpendicular.

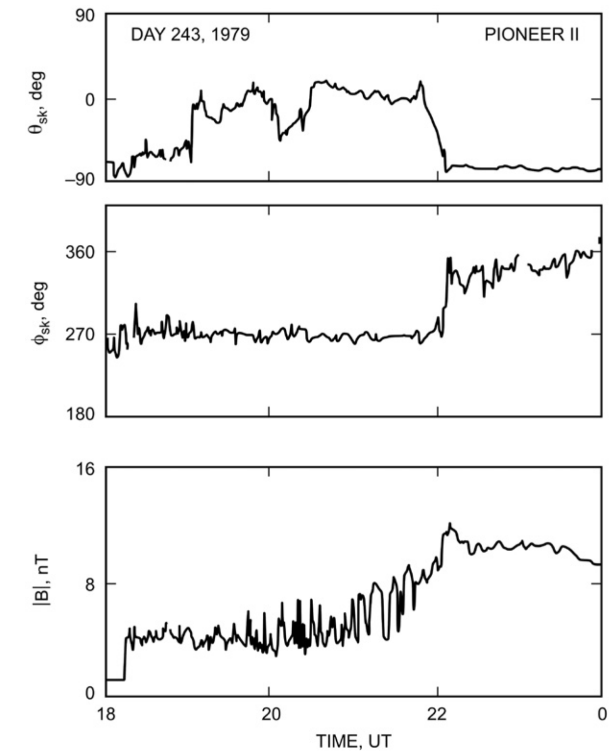

Fig. 4. MM structures in the magnetosheath of Saturn (taken from Smith et al., 1980; Tsurutani et al., 1982). The bow shock and magnetopause are indicated. There is little or no indication of MMs just downstream of the bow shock. MMs first appear approximately 1/3 through the sheath and reach maximum amplitudes close to the magnetopause. There is no indication of saturation effects.

It is possible that the satellite did not enter the magnetosheath at the right position (see Du et al. (2009) for a detailed discussion of the location of instability in the Earth's magnetosheath). However another possibility is that the growth rate is slow in comparison to the convection speed. What is obvious (and typical) is that the MM structures continue to grow in amplitude all the way to the magnetopause. This can be understood by the continual feeding of free energy by the magnetic field draping process.

4.3. Do mirror mode structures form in ICME and CIR sheaths?

There have been very few reports of mirror instability in the heliosphere outside of planetary magnetosheaths. Tsurutani et al. (1992) have reported magnetic dips with $\sim 100\ \rho_p$ scale sizes that occurred in a high β region between two interplanetary forward shocks during the March 23–25, 1991 Ulysses event. Liu et al. (2006) have shown short intervals in ICME sheaths where the magnetic and plasma pressures are out-of-phase. The latter authors believe these structures are mirror modes. Recently Tsurutani et al. (2009) have examined CIR (and some ICME) sheaths and have found a general lack of the presence of MMs within them. The authors mention that MMs could form in interplanetary sheaths if the shocks were purely perpendicular, if the shocks are quasiperpendicular and the upstream plasma β is high (higher than 1.0), if the shocks are quasiperpendicular with high Mach number (>3), or if field line draping also occurs. It is possible that some of these conditions are held for the Tsurutani et al. (1992) and the Liu et al. (2006) cases. But the main point is that such occurrences in interplanetary space are quite rare. When MMs do occur, only a few cycles are typically generated.

5. Final comments

The physics generating MM structures in the heliosheath is a multistep process. It is also noted that MM instability in planetary magnetosheaths is likewise a multistep process. Comparisons between the two cases are helpful in understanding the overall mechanisms that drive the instability in the linear, nonlinear, and saturation phases (see Qu et al., 2008). The heliosheath is the best plasma laboratory/opportunity to understand this instability in the later stages. The plasma community awaits further Voyager information on deep heliosheath observations.

Acknowledgements

This paper contains work done at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. GSL thanks the Indian National Science Academy, New Delhi, for support under the Senior Scientist Scheme. EE acknowledges Brazilian FAPESP agency 2007/52533-1 for support of this work.

References

Anderson, B.J., Fuselier, S.A., 1993. 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.
Balogh, A., Beek, T.J., Forsyth, R.J., Hedgecock, P.C., Marquedant, R.J., Smith, E.J., Southwood, D.J., Tsurutani, B.T., 1992a. The magnetic field investigation on the Ulysses mission: instrumentation and preliminary results. Astron. Astrophys. Suppl. Ser. 92, 221.
Balogh, A., Dougherty, M.K., Forsyth, R.J., Southwood, D.J., Smith, E.J., Tsurutani, B.T., Murphy, N., Burton, M.E., 1992b. Magnetic field observations during the Ulysses flyby of Jupiter. Science 257, 1515.
Bavassano Cattaneo, M.B., Basile, C., Moreno, G., Richardson, J.D., 1998. Evolution of mirror structures in the magnetosheath of Saturn from the bow shock to the magnetopause. J. Geophys. Res. 103 (11), 961.
Brinca, A.L., Tsurutani, B.T., 1989. Influence of multiple ion species on low-frequency electromagnetic wave instabilities. J. Geophys. Res. 94 (A10), 13,565.
Burlaga, L.F., Lemaire, J.F., 1978. Interplanetary magnetic holes: theory. J. Geophys. Res. 83, 5157.
Burlaga, L.F., Ness, N.F., Acuna, M.H., 2006. Magnetic fields in the heliosheath: Voyager 1 observations. Astrophys. J. 642, 584.
Burlaga, L.F., Ness, N.F., Acuna, M.H., 2007. Linear magnetic holes in a unipolar region of the heliosheath observed by Voyager 1. J. Geophys. Res. 112, A07106. doi:10.1029/2007JA012292.
Burlaga, L.F., et al., 2008. Global structure and dynamics of large-scale fluctuations in the solar wind: Voyager 2 observations during 2005 and 2006. J. Geophys. Res. 113, A02104. doi:10.1029/2007JA012796.
Buti, B., Jayanti, V., Vinas, A.F., Ghosh, S., Goldstein, M.L., Roberts, D.A., Lakhina, G.S., Tsurutani, B.T., 1998. Nonlinear evolution of Alfven wave packets. Geophys. Res. Lett. 25, 2377.
Chandrasekhar, S.A., Kaufman, A.N., Watson, K.M., 1958. The stability of the pinch. Proc. R. Soc. Lond. Ser. A 245, 435.
Du, J., Wang, C., Zhang, T.L., Volwerk, M., Carr, C., 2009. Mirror waves and mode transition observed in the magnetosheath by Double Star TC-1. Ann. Geophys. 27, 351.
Dunlop, M.W., Lucek, E.A., Kistler, L.M., Cargill, P., Balogh, A., Baumjohann, W., 2002. Equator-S observations of ion cyclotron waves outside the dawnside magnetopause. J. Geophys. Res. 107. doi:10.1029/2001JA900170.
Erdos, G., Balogh, A., 1996. Statistical properties of mirror mode structures observed by Ulysses in the magnetosheath of Jupiter. J. Geophys. Res. 101, 1.
Fahr, H.-J., Chalov, S.V., 2008. Supersonic solar wind ion flows downstream of the termination shock explained by a two-fluid shock model. Astron. Astrophys. 490, L35. doi:10.1051/0004-6361:200810679.
Farrugia, C.J., Vasquez, B., Richardson, I.G., Torbert, R.B., Burlaga, L.F., Biernat, H.K., Muhlbachler, S., Ogilvie, K.W., Lepping, R.P., Scudder, J.D., Berdichevsky, D.E., Semenov, V.S., Kubyshikin, I.V., Phan, T.D., Lin, R.P., 2001. A reconnection layer associated with a magnetic cloud. Adv. Space Res. 28, 759.
Fränz, M., Burgess, D., Horbury, T.S., 2000. Magnetic depressions in the solar wind. J. Geophys. Res. 105 (12), 725.
Genot, V., 2008. Mirror and firehose instabilities in the heliosheath. Astrophys. J. 687, L119.
Hasegawa, A., 1969. Drift mirror instability in the magnetosphere. Phys. Fluids 12, 2642.
Hasegawa, A., 1975. Plasma instabilities and nonlinear effects. Physics and Chemistry in Space, vol. 8. Springer-Verlag, New York, p. 94.
Hau, L.-N., Wang, B.-J., Teh, W.-L., 2005. Slow mode waves and mirror instability in gyrotropic Hall magnetohydrodynamic model. Phys. Plasmas 12, 122904-1.
Hellinger, P., 2008. Comment on the drift mirror instability. Phys. Plasmas 15, 054502-1.
Horbury, T.S., Lucek, E.A., Balogh, A., 2004. Motion and orientation of magnetic field dips and peaks in the terrestrial magnetosheath. J. Geophys. Res. 109, A09209. doi:10.1029/2003JA010237.
Horbury, T.S., Lucek, E.A., 2009. Size, shape, and orientation of magnetosheath mirror mode structures. J. Geophys. Res. 114. doi:10.1029/2009JA014068.
Klimushkin, Chen, 2006. Eigenmode stability analysis of drift-morror modes in nonuniform plasmas. Ann. Geophys. 24, 2435.
Lacombe, C., Pantellini, F.G.E., Hubert, D., Harvey, C.C., Mangeney, A., Belmont, G., Russell, C.T., 1992. Mirror and Alfvenic waves observed by ISEE 1-2 during crossings of the Earth's bow shock. Ann. Geophys. 10, 772.
Leubner, M.P., Schupfer, N., 2000. Mirror instability thresholds in suprathermal space plasmas. J. Geophys. Res. 105 (A12), 27387.
Liu, Y., Richardson, J.D., Belcher, J.W., Kasper, J.C., Skoug, R.M., 2006. Plasma depletion and mirror waves ahead of interplanetary coronal mass ejections. J. Geophys. Res. 111, A09108. doi:10.1029/2006JA011723.
Liu, Y., Richardson, J.D., Belcher, J.W., Kaspar, J.C., 2007. Temperature anisotropy in a shocked plasma: mirror-mode instabilities in the heliosheath. Astrophys. J. 659, L65.
Lucek, E.A., Dunlop, M.W., Balogh, A., Cargill, P., Baumjohann, W., Georgescu, E., Haerendel, G., Fornacon, K.-H., 1999a. Identification of magnetosheath mirror modes in Equator-S magnetic field data. Ann. Geophys. 17, 1560.
Lucek, E.A., Dunlop, M.W., Balogh, A., Cargill, P., Baumjohann, W., Georgescu, E., Haerendel, G., Fornacon, K.-H., 1999b. Mirror mode structures observed in the dawn-side magnetosheath by Equator-S. Geophys. Res. Lett. 26, 2159.
Lucek, E.A., Dunlop, M.W., Horbury, T.S., Balogh, A., Brown, P., Cargill, P., Carr, C., Fornacon, K.-H., Georgescu, E., Oddy, T., 2001. Cluster magnetic field observations in the magnetosheath: four-point measurements of mirror structures. Ann. Geophys. 19, 1421.
Midgley, J.E., Davis Jr., L., 1963. Calculation by a moment technique of the perturbation of the geomagnetic field by the solar wind. J. Geophys. Res. 68, 5111.
Migliuolo, S., 1986. The field swelling and mirror modes: connection of the two instabilities. J. Geophys. Res. 91, 7981.
Narita, Y., Glassmeier, K.-H., 2005. Dispersion analysis of low-frequency waves through the terrestrial bow shock. J. Geophys. Res. 110. doi:10.1029/2005JA011256.
Neugebauer, M., Goldstein, B.E., Winterhalter, D., Smith, E.J., McDowell, R.J., Gary, S.P., 2001. Ion distribution in large magnetic holes in the fast solar wind. J. Geophys. Res. 106, 5635.
Pokhotelov, O.A., Sagdeev, R.Z., Balikhin, M.A., Treumann, R.A., 2004. Mirror instability at finite ion-Larmor radius wavelengths. J. Geophys. Res. 109, A09213. doi:10.1029/2004JA010568.
Pokhotelov, O.A., Sagdeev, R.Z., Balikhin, M.A., Treumann, R.A., 2005. Comment on theory and observations of slow-mode solitons in space plasmas. Phys. Rev. Lett. 95, 129501-1.
Pokhotelov, O.A.R.Z., Sagdeev, M.A., Balikhin, O.G., Onishchenko, Fedun, V.N., 2008. Nonlinear mirror waves in non-Maxwellian space plasmas. J. Geophys. Res. 113. doi:10.1029/2007JA012642.
Qu, H., Lin, Z., Chen, L., 2008. Nonlinear saturation of mirror instability. Geophys. Res. Lett. 35, L10108. doi:10.1029/2008GL033907.
Price, C.P., Swift, D.W., Lee, L.-C., 1986. Numerical simulation of nonoscillatory mirror mode waves at the Earth's magnetosheath. J. Geophys. Res. 91, 101.
Richardson, J.D., 2008. Plasma near the termination shock and the heliosheath. In: Li, G. (Ed.), CP1029, Particle Acceleration and Transport in the Heliosphere and Beyond…7th Annual Astrophysics Conference. American Institute of Physics, NY.
Richardson, J.D., Stone, E.C., 2008. The solar wind in the outer heliosphere. Space Sci. Rev.. doi:10.1007/s11214-008-9443-z.
Russell, C.T., Riedler, W., Schwingenschuh, K., Yeroshenko, Y., 1987. Mirror instability in the magnetosphere of comet Halley. Geophys. Res. Lett. 14, 644.
Shapiro, V.D., Shevchenko, V.I., 1964. Quasilinear theory of instability of a plasma with an anisotropic ion velocity distribution. Soviet Phys. JETP 18 (4), 1109.
Shoji, M., Omura, Y., Tsurutani, B.T., Verkhoglyadova, O.P., Lembege, B., 2009. Mirror instability and L-mode electromagnetic ion cyclotron instability: competition in the Earth's magnetosheath. J. Geophys. Res. 114, A102203. doi:10.1029/2008JA014038.
Smith, E.J., Davis Jr., L., Jones, D.E., Coleman Jr., P.J., Colburn, D.S., Dyal, P., Sonett, C.P., 1980. Saturn's magnetosphere and its interaction with the solar wind. J. Geophys. Res. 85, 5655.
Southwood, D.J., Kivelson, M.G., 1993. Mirror instability: 1. Physical mechanism of linear instability. J. Geophys. Res. 98, 9181.
Stasiewicz, K., Shukla, P.K., Gustafsson, G., Buchert, S., Lavraud, B., Thide, B., Klos, Z., 2003. Phys. Rev. Lett. 90, 085002.
Tátrallyay, M., Erdos, G., 2002. The evolution of mirror mode fluctuations in the terrestrial magnetosheath. Planet. Spa. Sci. 50, 593.
Tátrallyay, M., Erdos, G., 2005. Statistical investigation of mirror type magnetic depressions observed by ISEE-1. Planet. Spa. Sci. 53, 33.

Tsurutani, B.T., Rodriguez, P., 1981. Upstream waves and particles: an overview of ISEE results. J. Geophys. Res. 86, 4319.

Tsurutani, B.T., Ho, C.M., 1999. A review of discontinuities and Alfvén waves in interplanetary space: Ulysses results. Rev. Geophys. 37, 517.

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

Tsurutani, B.T., Richardson, I.G., Lepping, R.P., Zwickl, R.D., Jones, D.E., Smith, E.J., Bame, S.J., 1984. Drift mirror waves in the distant (X=200 R_e) magnetosheath. Geophys. Res. Lett. 11, 1102.

Tsurutani, B.T., Southwood, D.J., Smith, E.J., Balogh, A., 1992. Nonlinear magnetosonic waves and mirror mode structures in the March 1991 Ulysses interplanetary event. Geophys. Res. Lett. 19, 1267.

Tsurutani, B.T., Southwood, D.J., Smith, E.J., Balogh, A., 1993. A survey of low frequency waves at Jupiter: the Ulysses encounter. J. Geophys. Res. 98 (21), 203.

Tsurutani, B.T.G.S., Lakhina, E.J., Smith, B., Buti, S.L., Moses, F.V., Coroniti, A.L., Brinca, J.A., Slavin, Zwickl, R.D., 1999. Mirror mode structures and ELF plasma waves in the Giacobini-Zinner magnetosheath. Nonl. Proc. Geophys. 6, 229.

Tsurutani, B.T., Dasgupta, B., Galvan, C., Neugebauer, M., Lakhina, G.S., Arballo, J.K., Winterhalter, D., Goldstein, B.E., Buti, B., 2002a. Phase-steepened Alfvén waves, proton perpendicular energization and creation of magnetic holes and magnetic decreases: the ponderomotive force. Geophys. Res. Lett. 29, 86-1. doi:10.1029/2002GL015652.

Tsurutani, B.T., Galvan, C., Arballo, J.K., Winterhalter, D., Sakurai, R., Smith, E.J., Buti, B., Lakhina, G.S., Balogh, A., 2002b. Relationship between discontinuities, magnetic holes, magnetic decreases, and nonlinear Alfven waves: Ulysses observations over the solar poles. Geophys. Res. Lett. 29, 23-1. doi:10.1029/2001GL013623.

Tsurutani, B.T., Guarneiri, F.L., Echer, E., Lakhina, G.S., Verkhoglyadova, O.P., 2009. Magnetic decrease (MD) formation from <1 to ~ 5 AU: co-rotating interaction region reverse shocks. J. Geophys. Res. 114, A08105. doi:10.1029/2008JA013927.

Turner, J.M., Burlaga, L.F., Ness, N.F., Lemaire, J.F., 1977. Magnetic holes in the solar wind. J. Geophys. Res. 82, 1921.

Vedenov, A.A., Sagdeev, R.Z., 1958. Some properties of a plasma with an anisotropic ion velocity distribution in a magnetic field. Plasma Phys. Prob. Controlled Thermo. Reacts., vol. 3. Pergamon, p. 332.

Violante, L., Cattaneo, B.M.B., Moreno, G., Richardson, J.D., 1995. Observations of mirror waves and plasma depletion layer upstream of Saturn's magnetopause. J. Geophys. Res. 100 (12), 047.

Volwerk, M.T.L., Zhang, M., Delva, Z., Voros, W., Baumjohann, Glassmeier, K.-H., 2008a. First identification of mirror mode waves in Venus' magnetosheath? Geophys. Res. Lett. 35 L12204. doi:10.1029/2008GL033621.

Volwerk, M.T.L., Zhang, M., Delva, Z., Voros, W., Baumjohann, Glassmeier, K.-H., 2008b. Mirror mode-like structures in Venus' induced magnetosphere. J. Geophys. Res. 113, E00B16. doi:10.1029/2008JE003154.

Winterhalter, D., Neugebauer, M., Goldstein, B.E., Smith, E.J., Bame, S.J., Balogh, A., 1994. Ulysses field and plasma observations of magnetic holes in the solar wind and their relation to mirror-mode structures. J. Geophys. Res. 99, 23, 371.

Winterhalter, D., Neugebauer, M., Goldstein, B.E., Smith, E.J., Tsurutani, B.T., Bame, S.J., Balogh, A., 1995. Magnetic holes in the solar wind and their relation to mirror-mode structures. Space Sci. Rev. 72, 201.

Zhang, T.L., Baumjohann, W., Russell, C.T., Jian, L.K., Wang, C., Cao, J.B., Balikhin, M., Blanco-Cano, X., Delva, M., Volwerk, M., 2009. Mirror mode structures in the solar wind at 0.72 AU. J. Geophys. Res. 114, A10107. doi:10.1029/2009JA014103.

Zwan, B.J., Wolf, R.A., 1976. Depletion of the solar wind plasma near a planetary boundary. J. Geophys. Res. 81, 1636.