Mirror Modes in the Heliosheath

Article · January 2011

DOI: 10.1063/1.3544315

5 authors, including:

F. L. Guarnieri
149 PUBLICATIONS **4,051** CITATIONS
SEE PROFILE

E. Echer
National Institute for Space Research, Brazil
383 PUBLICATIONS **5,806** CITATIONS
SEE PROFILE

G. S. Lakhina
Indian Institute of Geomagnetism
313 PUBLICATIONS **6,429** CITATIONS
SEE PROFILE

Olga Verkhoglyadova
NASA
239 PUBLICATIONS **3,979** CITATIONS
SEE PROFILE

Mirror Modes in the Heliosheath

B.T. Tsurutani,[1] F.L. Guarnieri,[2] E.E. Echer,[3] G.S. Lakhina,[4]
and O.P. Verkhoglyadova

[1]Jet Propulsion Lab., Calif. Inst. Tech., Pasadena, CA
[2]UNIVAP, Sao Jose dos Campos, SP, Brazil
[3]INPE, Sao Jose dos Campos, SP, Brazil
[4]Indian Institute of Geomagnetism, Navi Mumbai, India
[5]CSPAR, Univ. Alabama, Huntsville, AL

Abstract. Mirror mode (MM) structures are identified in the Voyager 1 heliosheath magnetic field data. Their characteristics are: 1) quasiperiodic structures with a typical scale size of ~57 ρ_p (proton gyroradii), 2) little or no angular changes across the structures (~3° longitude and ~3° latitude), and 3) a lack of sharp boundaries at the magnetic dip edges. It is proposed that the pickup of interstellar neutrals in the upstream region of the termination shock (TS) is the likely cause of MM instability during intervals when the IMF is nearly orthogonal to the solar wind flow direction. Concomitant (quasiperpendicular) shock compression of the MM structures at the TS and additional injection of pickup ions (PUIs) throughout the heliosheath will enhance MM growth.

Keywords: Nonlinear waves, pickup ions, heliosheath, Voyager spacecraft, collisionless shocks.
PACS: 96.50.Ci, 96.50.Bh, 96.50.Xy, 96.50.Ya, 52.35.Tc.

PROLOGUE

This paper is dedicated to Konstantinos (Dennis) Papadopoulos. There have been many testimonials made as to the brilliant physical insights that Dennis has brought to our field. We are in total agreement with this sentiment. However Dennis has made far broader contributions than just his expertise in plasma physics. He has a world experience that he also brings to our community. We would like to mention an example of Dennis' helpfulness in this greater viewpoint.

About 30 years ago, after the launch of the three NASA/ESA International Sun Earth Explorer (ISEE) spacecraft, a number of us ISEE scientists thought it would be a good idea to have a meeting on the topic of collisionless shock waves. We approached Dennis, whom we knew was *the* expert in plasma instabilities at shocks and also was widely traveled. We asked him for a suggestion for a good place for a Chapman meeting. Dennis mentioned Napa Valley, CA, our back yard. Of course! This was an obvious setting to not only have good scientific discussions, but to have fun as well. After we obtained approval to have a Chapman Conference from the American Geophysical Union and found a nice place to hold the meeting (the Silverado Country Club), we asked ourselves what would Dennis do to bring some real fun for the Conference attendees? We did not want to have a straight 5 days of intense scientific discussions. We knew that the discussions would be heated, and we needed a break in the middle. We came up with the idea of a "business dinner". But where? Again we were stumped. Where should we have the dinner and what format should it take? Again we contacted Dennis. Dennis suggested the Etoile restaurant, where the Domaine Chandon winery is. We followed Dennis' suggestion and were extremely fortunate. The number of attendees was large enough that we could take over the whole winery and restaurant for the evening. We could start with a tour of the winery, try the (then) two Domaine Chandon champagnes and their aperitif after the tour, and then three more wines with dinner. But who would be an appropriate speaker at the dinner? After bouncing around a number of ideas, we took an (obvious) suggestion from Dennis: Tommy Gold.

The meeting and dinner went off as planned. Tommy Gold recounted his original ideas of a bow shock in front of the magnetosphere at the dinner review. He also mentioned that he was trying to convince Sweden to drill for oil (an idea which did not pan out). The meeting was intense (highly interactive), productive, and in hindsight, a lot of fun. Dennis wrote the review chapter on plasma instabilities at shocks for the AGU monograph. In recounting this to Dennis at the Halkidiki, Greece Conference, he did not remember that it was his suggestions that led to the meeting location, the dinner and the speaker for the Collisionless Shock Chapman Conference. We suspect that Dennis has also done similar things many times in his life. He generously "tosses out" lots of ideas for solutions to problems and then promptly forgets that he did this. However others have not forgotten his generosity, brilliance and helpfulness. We profusely thank Dennis for his contributions to plasma physics and we dedicate this paper to him.

INTRODUCTION

Significant, large-amplitude magnetic field magnitude dips have been detected in the heliosheath by Voyager 1 (Burlaga et al., 2006; 2008). The dips can be as large as 90% of the background field. We examine these structures to determine if they could possibly be due to the mirror mode instability.

Mirror mode (MM) structure growth occurs when the instability condition $\beta_\perp \beta_\parallel > 1 + 1/\beta_\perp$ is satisfied (Chandrasekhar et al., 1958; Vedenov and Sagdeev, 1958; Hasegawa, 1969; Price et al., 1986; Pokhotelov et al., 2004; Shoji et al., 2009). Here β ($8\pi nkT/B^2$) is the ratio of the plasma thermal pressure to the magnetic pressure. The subscripts "$\perp$" and "$\parallel$" refer to the components of the plasma pressure perpendicular and parallel to the ambient magnetic field B_0, respectively. The MMs are non-oscillatory (non-propagating) structures (Hasegawa, 1969; 1975) and are convected by the flowing plasma to first order (Tsurutani et al., 1982; Horbury et al., 2004).

Mirror mode structures have been identified in the magnetosheaths of Earth, Jupiter, Saturn and at comets (Tsurutani et al., 1982, 1984, 1993, 1999; Violante et al., 1995; Bavassano-Cataneo et al., 1998; Horbury and Lucek, 2009). MMs have been detected in interplanetary space (Tsurutani et al., 1992), but only rarely. From the above articles (and more), the properties of MM structures are: 1) they are quasiperiodic (convected) oscillations in $|B_0|$, 2) the scale size of the structures vary from 20 to 50 proton gyroradii 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, and 5) MMs are total-pressure balance structures.

The purpose of this letter is to examine the Voyager 1 heliosheath magnetic field data and to determine if these magnetic features are MM structures or not. If they are MM structures, the source(s) of "free energy" for the instability will be examined and identified.

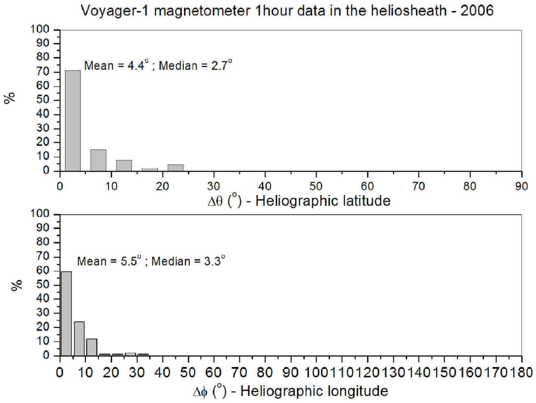

FIGURE 1. Histograms of the angular changes (in θ and φ) across the MM dips. The histograms are binned in 5º increments and the vertical scales are given in percent of the total. Ninty-six magnetic dips were selected at random and were used in these statistics.

RESULTS

Figure 1 gives quantitative results of a detailed examination of the angular changes across the Voyager 1 magnetic dips. 96 events from the 2006 data were studied using 1-hr average data. Dip-to-dip changes were measured. It is found that the latitudinal angular changes (Δθ) given in the top panel had a median of 2.7º with a mean of 4.4º. The longitudinal angular changes (Δφ) given in the bottom panel had a median of 3.3º and a mean of 5.5º.

Figure 2 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.

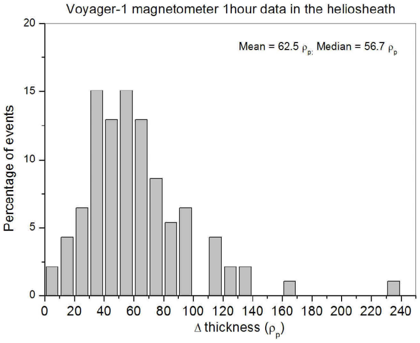

FIGURE 2. The distribution of the separation of the MM dips. The size is given in proton gyroradii (ρ_p).

Source of "Free Energy" for Heliosheath Mirror Instability

For the region upstream of the termination shock (TS), we use the following measured solar wind parameters: $N = 10^{-3}$ cm^{-3}, $B_0 = 5 \times 10^{-2}$ nT, and $T = 10^4$ K. 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). We assume that these same numbers apply for the Voyager 1 crossing (no plasma data is available). We will use a conservative value of 20% speed decrease. This implies a 25% increase in solar wind mass. This mass increase is due to the ionization and pickup of interstellar neutrals by the solar wind. This mass loading implies a pickup ion density of $N_{pickup} = 2.5 \times 10^{-4}$ cm^{-3}, assuming hydrogen ion (proton) pickup. The protons are assumed to gain ~1 keV in perpendicular kinetic energy by the pickup process. If we assume that the interplanetary magnetic field varies ~10º away from orthogonal due to the presence of long period Alfvénic fluctuations, the ratio of $\beta_\perp/\beta_\parallel$ will have a value of ~9, much larger than the instability criterion of ~1. For larger B_0 angular variations, this ratio will be lower. In any case, it is apparent that significant mass loading will trigger MM growth upstream of the TS.

If the upstream magnetic field is nearly perpendicular to the solar wind flow, the TS will be quasi-perpendicular. The upstream MM structures will be convected into the TS and ion perpendicular heating from this compression will provide further free energy for MM growth. 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.

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 (not shown to save space), 3) have scale size of ~57 ρ_p, and 4) there is little or no change in B_0 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 mentioned that the pickup of ions and the TS shock compression will lead to density gradients and the possible appearance of a non-zero frequency of the mode (Pokhotelov et al., 2003). It will be interesting to determine if this is present or not. It will also be interesting to examine the MM structures deeper in the heliosheath. What will the nonlinear saturation look like?

ACKNOWLEDGMENTS

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

REFERENCES

1. Bavassano Cattaneo, M.B., C. Basile, G. Moreno and J.D. Richardson, Evolution of mirror structures in the magnetosheath of Saturn from the bow shock to the magnetopause, *J. Geophys. Res., 103*, 11,961, 1998.
2. Burlaga, L.F., N.F. Ness and M.H. Acuna, Magnetic fields in the heliosheath: Voyager 1 observations, *Astrophys. J., 642*, 584, 2006.
3. Burlaga, L.F., et al., 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, 2008.
4. Chandrasekhar, S.A., A.N. Kaufman, and K.M. Watson, The stability of the pinch, *Proc. R. Soc. London Ser. A, 245*, 435, 1958.
5. Hasegawa, A., Drift mirror instability in the magnetosphere, *Phys. Fluids, 12*, 2642, 1969.
6. Hasegawa, A. *Plasma Instabilities and Nonlinear Effects*, Phys. and Chem. In Space 8, Springer-Verlag, Ney York, 94, 1975.
7. Horbury, T.S., E.A. Lucek, and A. Balogh, Motion and orientation of magnetic field dips and peaks in the terrestrial magnetosheath, *J. Geophys. Res., 109*, A09209, doi:10.1029/2003JA010237, 2004.
8. Horbury, T.S. and E.A. Lucek, Size, shape, and orientation of magnetosheath mirror mode structures, *J. Geophys. Res., 114*, doi:10.1029/2009JA014068, 2009.
9. Pokhotelov, O.A., I. Sandberg, R.Z. Sagdeev, R.A. Treumann, O.G. Onishchenko, M.A. Balikhin and V. P. Pavlenko, Slow drift mirror modes in finite electrontermperature plasmas: Hydrodynamic and kinetic

drift mirror instabilities, *J. Geophys.Res., 108*, A3, 1098, doi:10.1029/2002JA009651, 2003.

10. Pokhotelov, O.A., R.Z. Sagdeev, M.A. Balikhin and R.A. Treumann, Mirror instability at finite ion-Larmor radius wavelengths, *J. Geophys. Res., 109,* A09213, doi:10.1029/2004JA010568, 2004.
11. Price, C.P., D.W. Swift, and L.-C. Lee, Numerical simulation of nonoscillatory mirror mode waves at the Earth's magnetosheath, *J. Geophys. Res., 91*, 101, 1986.
12. Richardson, J.D. and E.C. Stone, The solar wind in the outer heliosphere, *Space Sci. Rev.*, doi:10.1007/s11214-008-9443-z, 2008.
13. Shoji, M., Y. Omura, B.T. Tsurutani, O.P. Verkhoglyadova and B. Lembege, Mirror instability and L-mode electromagnetic ion cyclotron instability: Competition in the Earth's magnetosheath, *J. Geophys. Res*., *114*, A10203, doi:10.1029/2008JA014038, 2009.
14. 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, 1982.
15. Tsurutani, B.T. I.G. Richardson, R.P. Lepping, R.D. Zwickl, D.E. Jones, E.J. Smith, S.J. Bame, Drift mirror mode waves in the distant (X = -200Re) magnetosheath, *Geophys. Res. Lett., 11*, 1102, 1984.
16. Tsurutani, B.T., D.J. Southwood, E.J. Smith, and A. Balogh, Nonlinear magnetosonic waves and mirror mode structures in the March 1991 Ulysses interplanetary event, *Geophys. Res. Lett., 19*, 1267, 1992.
17. Tsurutani, B.T., D.J. Southwood, E.J. Smith, and A. Balogh, A survey of low frequency waves at Jupiter: The Ulysses encounter, *J. Geophys. Res., 98*, 21,203, 1993.
18. Tsurutani, B.T. G.S. Lakhina, E.J. Smith, B. Buti, S.L. Moses, F.V. Coroniti, A.L. Brinca, J.A. Slavin and R.D. Zwickl, Mirror mode structures and ELF plasma waves in the Giacobini-Zinner magnetosheath, *Nonl. Proc. Geophys., 6*, 229, 1999.
19. Vedenov, A.A. and R.Z. Sagdeev, Some properties of a plasma with an anisotropic ion velocity distribution in a magnetic field, in *Plasma Phys. Prob. Controlled Thermo.Reacts. , 3*, 332, Pergamon, 1958.
20. Violante, L., B.M.B. Cattaneo, G. Moreno and J.D. Richardson, Observations of mirror waves and plasma depletion layer upstream of Saturn's magnetopause, *J. Geophys. Res., 100*, 12,047, 1995.