GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 21, PAGES 3587-3590, NOVEMBER 1, 2000

A simple model of complex cusp ion dispersions during intervals of northward interplanetary magnetic field

S. M. Topliss and C. J. Owen

Mullard Space Science Laboratory, Holmbury St. Mary, United Kingdom.

W. K. Peterson

Lockheed-Martin Palo Alto Research Lab., Palo Alto, California.

Abstract. During northward IMF intervals, cusp ion energy-latitude dispersions observed by POLAR's TIMAS instrument often have two components. One dispersion decreases in energy with decreasing latitude. The second appears to split from the first and increases in energy as the equatorward edge of the cusp is approached. We present a simple model representing particle entry resulting from reconnection poleward of the cusp. We qualitatively show that split dispersions may arise on reconnected field lines which accelerate as they contract sunward into regions of lower magnetosheath flow velocity. The velocity filter effect produces the first dispersion by spreading particles entering near the reconnection site across a range of latitudes. The second, increasing energy dispersion, results from particles crossing the magnetopause at later times and lower latitudes. These particles are accelerated to higher energies due to the increased contraction speed of reconnected field lines at these latitudes.

Introduction

During periods of northward Interplanetary Magnetic Field (IMF), the combination of high latitude reconnection, sunward convection, and the large thermal spread of magnetosheath ion velocities, can produce a velocity-dispersed cusp ion population [*Rosenbauer*, 1975], with ion energy decreasing with decreasing latitude. Sometimes at the equatorward edge of the cusp a reversed dispersion is seen, with energies increasing with decreasing latitudes [*Heikkila and Winningham*, 1971]. These split dispersions have been interpreted as evidence of solar wind plasma entry by cross-field diffusion, or quasi-simultaneous reconnection at both high and low latitudes [*Reiff et al.*, 1980]. Split dispersions at times of step-like changes in the IMF reported by *Yamauchi et al.* [1995] were interpreted as evidence for the wave-assisted cusp model of *Yamauchi and Lundin* [1994].

We present an observation from POLAR's TIMAS instrument [*Shelley et al.*, 1995] during a period of steady northward IMF. This reveals that when a second equatorward dispersion is observed, it splits from the main dispersion as its average energy increases. We describe a simple 2-D model of particle entry following reconnection poleward of the cusp. Model results show that a reconnected field line which accelerates as it moves sunward into regions of lower magnetosheath flow velocity can produce the split dispersions observed.

Observations

On October 2nd 1997, from 19:40 to 21:00 UT, POLAR moved equatorward through the northern polar cusp at 6-7 R_E altitude, slightly dawnward (10:50 to 11:30 MLT) of the noon-midnight meridian. Solar wind data from WIND [*Ogilvie et al.*, 1995; *Lepping et al.*, 1995], 5 R_E upstream of the dayside magnetopause show that IMF conditions were stable and strongly northward before and during this interval, with $\mathbf{B}_{GSM}$ = (-3,1,9) nT. The solar wind had density 3.5 cm^{-3}, dynamic pressure 1 nPa and flow speed 420 kms^{-1}.

POLAR TIMAS ion intensity spectrograms for H^+ and He^{++} integrated over all pitch angles are shown in the top two panels of Figure 1. Data are 24 seconds averaged (4 spins). A partial data gap occurred at 20:47 UT. The dominant ion population, seen from 19:40 to 20:55 UT, is composed of both H^+ and He^{++}. It is thus of solar wind/magnetosheath origin. Lower energy ionospheric H^+ populations are observed both before and after this time. As POLAR travels to lower latitudes, the low energy cut-off of the main magnetosheath population drops, consistent with plasma injection following reconnection poleward of the cusp and consequent sunward convection. From 20:23 to 20:42 UT, the magnetosheath population appears to split. The main distribution continues to lower energies, while a higher energy population forms. This new population increases slightly in energy and is observed until 20:55 UT, when a low flux, high energy magnetospheric H^+ population suggests that POLAR has moved on to closed field lines.

In a survey of 15 noon sector POLAR cusp crossings during steady northward IMF, 6 events show a relatively clear secondary magnetosheath population evolving at the equatorward edge of the cusp, with higher energies than the main population.

Paper number 2000GL000123.
0094-8276/00/2000GL000123$05.00

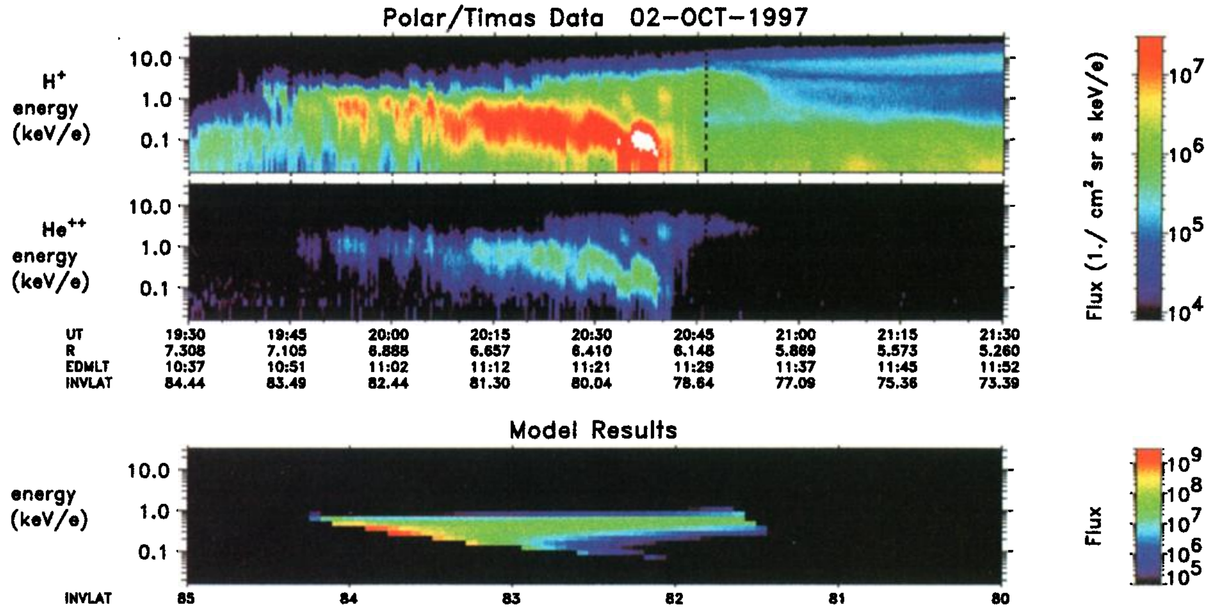

Figure 1. TIMAS H^+ and He^{++} spectrogram for 2^{nd} October 1997 and model results (bottom panel).

The Model

In this section, we develop a simple model simulating particle entry following reconnection poleward of the cusp. Similar models by *Lockwood* [1995] and *Onsager et al.* [1993] examined low-latitude reconnection. Our model predicts cusp energy-latitude ion dispersion signatures by considering particle entry into the magnetosphere coupled with convection and time-of-flight effects. Magnetosheath ions observed at a given cusp latitude cross the magnetopause over a range of downtail distances. While slow ions originate from near the neutral line, faster ions cross the magnetopause later and closer to the spacecraft. For high latitude reconnection, the magnetic tension of reconnected flux tubes may be opposed by a significant magnetosheath flow [*Cowley and Owen,* 1989], which usually increases with distance from the sub-solar point [*Sprieter and Stahara,* 1980]. Provided field lines can initially travel sunward, they may accelerate as they move into regions of reduced magnetosheath flow. Magnetosheath particles are also accelerated along reconnected cusp field lines as they cross the magnetopause. Higher field line contraction speeds will result in higher bulk flow speeds of the entering population. This effect can provide the high energy portion of the observed population, without affecting the low energy cut-off, which depends only on time-of-flight from the neutral line.

We consider a simplified, 2-D model, in which field lines threading out of the cusp and into the tail are represented as straight lines, as in Figure 2. Here the tail magnetopause is represented by the horizontal axis, while cusp latitude, or spacecraft trajectory, lies along the vertical axis. We locate the reconnection site at the position marked A. Consider a general spacecraft position at point C in the cusp. This is located on a field line, represented by the solid arrowed line, which instantaneously maps back to the magnetopause at position B. This field line has already convected some way sunward from the reconnection site. Magnetosheath particles observed at C must cross the magnetopause at points located between A and B, and have trajectories represented by the dotted lines. The fastest particles have trajectories that map back to the magnetopause close to B (although to actually originate from B particles would need infinite velocity). There will, however, be a low-energy cut-off, corresponding to the slowest particle which can enter at A and have time to reach C before the field line is swept over this position. For a given profile of convection speed of reconnected field lines away from the neutral line at A, it is straightforward to determine the magnetopause crossing location for particles of a given field-aligned speed V. The flux of these particles can be related to that of magnetosheath particles of similar energy which cross the magnetopause at that point.

The ion velocity distribution for sheath particles just inside the magnetopause can be determined from considerations of stress balance at the magnetopause [*Cowley,* 1982]. Figure 3 shows a velocity space diagram representing the high-latitude magnetopause . The V_x direction is tangential to the magnetopause while V_z is normal to this boundary. The unprimed frame (V_x, V_z) represents the Earth rest frame (ERF), and the primed frame (V_x', V_z') is the reconnected field line rest frame (FLRF). The FLRF is displaced by velocity V_f from the ERF, representing the field line contraction speed in the ERF. The thick arrowed line which reverses in V_x at the origin of the FLRF, represents a reconnected field line threading the magnetopause. This makes an angle θ to

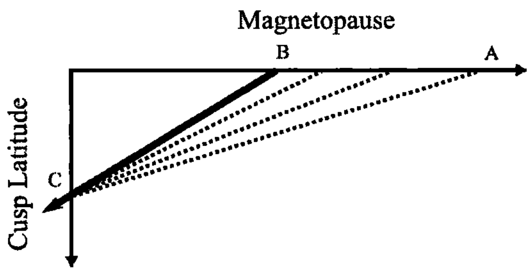

Figure 2. A two dimensional model layout. The thick black line represents a field line linking a point C in the cusp with point B on the magnetopause. Dotted lines are particle trajectories.

the V_x direction on the magnetospheric side of the magnetopause (lower half of diagram). The velocity space position of the centre of the magnetosheath population is labelled D. In the ERF, this moves with the bulk magnetosheath velocity V_{sh} in the direction shown. In the FLRF, the electric field is transformed away [*de Hoffman and Teller,* 1950], such that this population approaches the magnetopause along the sheath field direction. Also, the particles do not change speed during their interaction with the current sheet in this frame, so they emerge moving along the new field direction at the same distance from the origin of the primed frame. This point is marked E. Stress balance conditions [*Cowley and Owen,* 1989] suggest the bulk inflow and outflow speeds of the sheath population in the FLRF are both given by the magnetosheath Alfvèn speed, V_a. From geometry and using the small angle approximation cos $\theta \sim 1$, $V_f \sim V_a - V_{sh}$. In addition, the bulk speed of the particles entering the magnetosphere in the ERF is $V_p \sim V_f + V_a \sim 2V_a - V_{sh}$.

Note from these equations that in regions of high sheath flow V_{sh}, both the field line speed V_f and the bulk speed of the entering particles V_p are low. Since the magnetosheath is stagnant near the subsolar point, and increases in speed with distance tailward, it is reasonable to assume the field line and entry population speeds are slowest at locations closest to the reconnection site, and both increase as the reconnected flux tube convects sunward. Hence, higher speed cusp particles, which are sourced from a population crossing the magnetopause further sunward, undergo a greater acceleration and may thus have higher flux than expected from a constant magnetosheath velocity model.

Model Inputs

We combine *Spreiter and Stahara* [1980] gasdynamic parameters with solar wind conditions measured on October 2^{nd} 1997 to calculate the initial density (5.3 cm^{-3}) and temperature (4.1 x 10^6 K) of the magnetosheath ion population and to determine the initial (315 kms^{-1}) and final (170 kms^{-1}) V_{sh} along our model magnetopause. We decrease V_{sh} linearly between these values. We keep V_a constant at 350 kms^{-1}. We set the reconnection site at a field-aligned distance of 15 R_E above POLAR and consider particle entry along a distance of 10 R_E along the magnetopause. As the field lines travel this distance, we reduce the density of the plasma crossing the magnetopause, assuming that the solar wind portion of the reconnected field line is swept towards dawn or dusk and dragged antisunward. Our model considers only field-aligned ions, neglecting mirrored or ionospheric populations. More sophisticated models would, however, include the effect of density and magnetic field variation on V_a, and examine in more detail the way that V_{sh} varies along the magnetopause. For example, the magnetosheath flow will differ from simple gas-dynamics due to magnetic field effects.

Model Results

The bottom panel of Figure 1 shows the model output based on the inputs above, with latitude along the x-axis. A clear dispersion with energy decreasing with decreasing latitude is seen from 84.5° to 82° latitude, and from ~ 83° latitude a second, higher energy, dispersion can be seen with energy increasing with decreasing latitude. Densities are over an order of magnitude higher in our model than in the TIMAS spectrogram. This may indicate that the *Spreiter and Stahara* model predicts too large initial sheath densities. The gas-dynamic model neglects plasma depletion layer effects which may result in a density reduction as field lines drape over the magnetopause prior to reconnection [*Zwan and Wolf,* 1976]. We have assumed a magnetopause transmission coefficient of unity which may also result in an overestimate of cusp flux levels, although we are unaware of any empirical determination of typical magnetopause transmission coefficients.

The modelled lower latitude dispersion does not quantitatively match the POLAR data. This may be due to several reasons. Firstly, we assumed a constant field line convection velocity in the cusp. Real variations in convection velocity would, however, stretch or compress

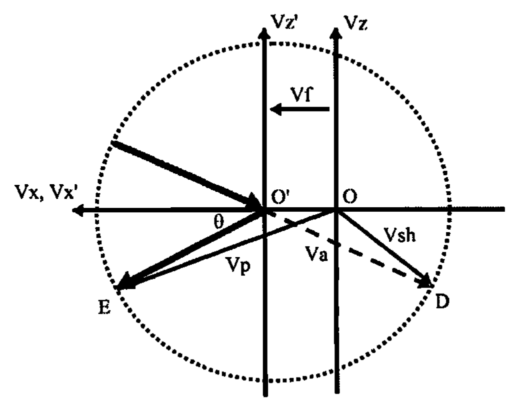

Figure 3. A velocity space plot in the Earth's rest frame (V_x, V_z) and the de-Hoffman Teller frame (V_x', V_z') showing field-aligned bulk flow at a rotational discontinuity at the magnetopause. The thick arrowed line with a kink at O', represents a reconnected field line threading through the magnetopause (V_x axis). Points D and E mark the velocity space position of the centre of the magnetosheath population before, and after crossing the magnetopause, respectively.

parts of the dispersion signatures in latitude. This may result in a more quantitative fit in latitudes between modelled and observed dispersion signatures. Secondly, a more sudden reversed energy dispersion at the equatorward edge of the cusp would also be created by, e.g., an exponential rather than linear increase in V_{sh} along the magnetopause. Gas-dynamic models do not, however, suggest such a sharp change in magnetosheath velocities over this distance. Thirdly, the density reduction in our model would actually increase V_a along the magnetopause, increasing particle acceleration and emphasising the reversed dispersion feature. The Alfvèn speed may also increase as reconnected field lines travelling sunwards encounter greater magnetic compression at the magnetopause [*Crooker et al.*, 1982]. More sophisticated models need to assess these effects. Despite these quantitative discrepancies, we have shown theoretically that split dispersions can be created from a single, high latitude reconnection site if sheath flow speed and/or Alfvèn speed variation is taken into account. Reasonable variation of input parameters does not change the general model results.

Summary and Conclusions

Split cusp ion energy dispersions during periods of northward IMF have been previously interpreted as evidence of solar wind entry into the magnetosheath by cross-field diffusion. We present a similar dispersion observed by POLAR, showing that the second, higher energy dispersion appears to split from the first.

By modelling particle entry across the open magnetopause sunward of a high latitude reconnection site, we have shown that a reconnected field line which accelerates as it moves sunward into regions of lower magnetosheath flow velocity can produce the split dispersions observed. The main energy-latitude dispersion is a result of sunward convection spreading the distribution of magnetosheath ions originating near the reconnection site over a range of cusp latitudes, with higher energy particles at higher latitudes. The reversed dispersion at lower latitudes is made up of magnetosheath ions which have crossed the magnetopause further sunward than ions in the main dispersion. These ions are accelerated to higher velocities at the magnetopause due to the increased field line contraction speed at the magnetopause. We note that a magnetosheath Alfvèn speed which increases in the sunward direction due to density reduction and/or increasing magnetic field may also explain the increasing energy of this secondary dispersion.

Acknowledgments. SMT and CJO were supported by a PPARC Studentship and Advanced Fellowship respectively. WKP was supported by NASA contract NAS5-30302 and thanks Dan Baker and the staff at LASP for their hospitality. We acknowledge the use of WIND kp data.

References

Cowley, S. W. H., The causes of convection within the earth's magnetosphere: a review of developments during the IMS, *Rev. Geophys. Space Phys.*, *20*, 531, 1982.

Cowley, S. W. H., and C. J. Owen, A simple illustrative model of open flux tube motion over the dayside magnetopause, *Planet. Space Sci.*, *37*, 1461, 1989.

Crooker, N. U., et al., Magnetic field compression at the dayside magnetopause, *J. Geophys. Res.*, *87*, 10407, 1982.

de Hoffman, F., and E. Teller, Magneto-hydrodynamic shocks, *Phys. Rev.*, *80*, 692, 1950.

Heikkila, W.J., and J.D. Winningham, Penetration of magnetosheath plasma to low altitudes through the dayside magnetospheric cusps, *J. Geophys. Res.*, *76*, 883, 1971.

Lepping, R. P., et al., The Wind magnetic field investigation, *Space Sci. Rev.*, *71*, 207, 1995.

Lockwood, M., Location and characteristics of the reconnection X line deduced from low-altitude satellite and ground-based observations 1. Theory, *J. Geophys. Res.*, *100*, 21791, 1995.

Ogilvie, K. W., et al., A comprehensive plasma instrument for the Wind spacecraft, *Space Sci. Rev.*, *71*, 55, 1995.

Onsager, T. G., et al., Model of magnetosheath plasma in the magnetosphere: cusp and mantle particles at low-altitudes, *Geophys. Res. Lett.*, *20*, 479, 1993.

Reiff, P.H., et al., Cusp proton signatures and the interplanetary magnetic field, *J. Geophys. Res.*, *85*, 5997, 1980.

Rosenbauer, H., HEOS 2 plasma observations in the distant polar magnetosphere: the plasma mantle, *J. Geophys. Res.*, *80*, 2723, 1975.

Shelley, E. G., et al., The toroidal imaging mass-angle spectrograph (TIMAS) for the POLAR mission, *Space. Sci. Rev.*, *71*, 497, 1995.

Sprieter, J. R., and S. S. Stahara, A new predictive model for determining solar wind-terrestrial planet interactions, *J. Geophys. Res.*, *85*, 6769, 1980.

Yamauchi, M. and R. Lundin, Classification of large-scale and meso-scale ion dispersion patterns observed by Viking over the cusp-mantle region, in *Physical signatures of magnetospheric boundary layer process*, edited by J. A. Holtet, and A. Egeland, 99, Kluwer Academic Publishers, Dordrecht, Netherlands, 1994.

Yamauchi, M. et al., Dynamic response of cusp morphology to the interplanetary magnetic field changes: An example observed by Viking, *J. Geophys. Res.*, *100*, 7661, 1995.

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

C. J. Owen and S. M. Topliss, Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, United Kingdom.

W. K. Peterson, Lockheed-Martin Palo Alto Research Lab., 3251 Hanover Street, Palo Alto, CA 94304.

(Received May 26, 2000; revised July 24, 2000; accepted July 31, 2000.)