

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

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Abstract. During extended intervals of northward interplanetary magnetic field, ion energy-latitude dispersions observed by polar orbiting satellites frequently consist of two distinct components. One dispersion decreases in energy equatorward from the poleward edge of the cusp, whilst another dispersion decreases in energy poleward from the equatorward edge. We present an example of such a dispersion seen in data by the TIMAS instrument on POLAR. We find that the second equatorward dispersion appears to split from the first main dispersion as its average energy increases. We present a simple two-dimensional model which simulates particle entry from a reconnection site at latitudes poleward of the cusp. We qualitatively show that a reconnected field line which accelerates as it moves sunward into regions of lower magnetosheath flow velocity can give rise to the split dispersions observed.

Introduction

During periods of northward Interplanetary Magnetic Field (IMF), the combination of high latitude reconnection, sunward convection, and finite and distinctly different velocities of solar wind plasma constituents, can give rise to a velocity dispersed cusp ion population [Rosenbauer, 1975], where higher energy ions are observed at higher latitudes in the cusp. Sometimes at the equatorward edge of the cusp a reversed dispersion is seen, with energies increasing with decreasing latitudes [e.g. Heikkila and Winningham, 1971]. These split dispersions have been interpreted as evidence of cross-field diffusion entry by solar wind plasma, or quasi-simultaneous reconnection at both high and low latitudes [Reiff *et al.*, 1980].

In this letter we first present an observation from the TIMAS instrument [*Shelley et al.*, 1995] onboard POLAR. This reveals that when a second equatorward dispersion is observed, it appears to split from the main dispersion as its average energy increases. We then describe a simple two- dimensional model of particle entry from a reconnection site at latitudes poleward of the cusp. Finally, we present results from the model, which show that a reconnected field line which accelerates as it moves sunward into regions of lower magnetosheath flow velocity can give rise to the split dispersions observed.

Observations

On the 2nd October 1997, from 19:40 to 21:00 UT, POLAR moved through the northern hemisphere polar cusp towards decreasing latitudes, at 6-7 R_e altitude. Its trajectory took it 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] shows that the IMF conditions were stable and strongly northward before and during POLAR's cusp encounter, with IMF $B_x = -3$ nT, $B_y = 1$ nT and $B_z = 9$ nT. During this period, the solar wind had density 3.5 cm^{-3} , dynamic pressure 1 nPa and flow speed 420 km s^{-1} .

POLAR TIMAS proton intensity spectrograms for H^+ and He^{++} integrated over all pitch angles are shown in Figure 1. Data has been averaged over 24 seconds (4 spins). The vertical black dotted line at 20:47 is a partial data gap. From this figure, it is clear that the dominant ion population seen from 19:40 to 20:55 UT, is composed of both H^+ and He^{++} . It is thus interpreted as being of solar wind/magnetosheath origin. Lower energy ionospheric H^+ populations are observed both before and after this time, and after 20:55 a low flux, high energy magnetospheric H^+ population suggests that POLAR has now moved on to closed field lines. As POLAR travels to lower latitudes, the low energy cut-off of the main magnetosheath population drops, consistent with solar wind plasma injection from a

reconnection site poleward of the cusp. From 20:23 to 20:42 UT, the magnetosheath population appears to split, with the main distribution continuing to lower energies, whilst a higher energy population forms. This new population increases in energy slightly and is observed until 20:55 UT.

A survey of 15 noon sector POLAR cusp crossings for periods of steady northward IMF, reveals 6 events showing a relatively clear secondary magnetosheath population evolving at the equatorward edge of the cusp, with higher energies than the main population.

The Model

In this section, we develop a simple two-dimensional model simulating particle entry from a reconnection site at latitudes poleward of the cusp. This model is similar to those described by *Lockwood* [1995] and *Onsager et al.* [1993] for low-latitude reconnection. Magnetosheath ions observed by a spacecraft at a given latitude in the cusp will have crossed the magnetopause over a range of downtail distances. Whilst the slow ions will have originated from near the neutral line, faster ions will have crossed the magnetopause more recently, closer to the spacecraft. At a high latitude reconnection site, the magnetic tension in the reconnected flux tubes may be opposed by a significant magnetosheath flow, which is known to increase with distance from the sub-solar point. Provided that field lines can initially travel sunward, they may accelerate as they move sunward into regions of reduced magnetosheath flow. Under these conditions, magnetosheath particles entering the magnetosphere along reconnected cusp field lines are also accelerated as they cross the magnetopause. Higher field line speeds will result in higher bulk flow speeds of the entering magnetosheath population. Here we demonstrate that this effect can provide the high energy portion of the observed population, without affecting the low energy cut-off which depends only on the time of flight from the neutral line.

We consider a simplified, two-dimensional model, in which the field lines threading out of the cusp and into the tail are represented as straight lines, as shown in Figure 2. In this manner, the tail magnetopause is represented by the horizontal x-axis, while the cusp latitude, representing the spacecraft trajectory, lies along the vertical y-axis. We locate the reconnection site at the far right of the diagram, at the position marked A. We now consider a general position for the spacecraft at a 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 points A and B, and have trajectories represented by the dotted lines in Figure 2. The highest speed particles will have trajectories that map back to the magnetopause close to the point B. There will, however, be a low-energy cut-off, which corresponds to the slowest particle which can enter the magnetosphere 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 the reconnected field line away from the neutral line at A, it is straightforward in this model 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 readily determined from considerations of stress balance at the magnetopause [e.g *Cowley*, 1982]. Figure 3 shows a velocity space diagram representing the high-latitude magnetopause considered here. The V_x direction is tangential to the magnetopause while the V_z direction is normal to this boundary. The unprimed frame (V_x, V_z) represents the Earth frame, and the primed frame (V_x', V_z') represents the frame in which the reconnected field line is at rest. This latter frame is displaced by a velocity V_f from the primed frame, representing the speed

of field line motion in the Earth frame. The thick arrowed line represents a reconnected field line threading the magnetopause and making an angle θ to the V_x direction. Note, however, that we make the small angle approximation such that $\cos \theta \sim 1$. We have also marked the velocity space position of the centre of the magnetosheath population as position D. In the Earth frame, this moves with the bulk magnetosheath velocity V_{sh} along the direction shown. In the field line rest frame, the electric field is transformed away [*de Hoffman and Teller*, 1950], such that this population must move into the magnetopause current sheet along the sheath field direction. In addition, the absence of an electric field dictates that, in this frame, the particles do not change speed during their interaction with the current sheet, such that 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 [e.g. *Cowley and Owen*, 1989] suggest that the bulk inflow and outflow speeds of the sheath population in the field line rest frame is simply the magnetosheath Alfvén speed, V_a , as marked in the figure. From geometrical considerations, and using the small angle approximation, it is clear that $V_f \sim V_a - V_{sh}$. In addition, in the Earth rest frame, the bulk speed of the particles entering the magnetosphere is shown by the line marked V_p in Figure 3, and we see from geometry that $V_p \sim V_f + V_a \sim 2V_a - V_{sh}$.

Note that both the field line speed V_f , and the bulk speed of the entering particles V_p , are low when the sheath flow V_{sh} is high. Since the magnetosheath is observed to be stagnant near the subsolar point, and increases in speed with distance tailward, it is reasonable to assume in our model that the field line and entry population speeds are slowest at locations closest to the reconnection site, and that both increase as the reconnected flux tube convects sunward. As a result, higher speed particles in the cusp, which are sourced from a population crossing the magnetopause at the more sunward locations, undergo a greater degree of acceleration and

may thus also have a higher flux than would be expected from a constant magnetosheath velocity model.

Model Inputs

We have combined *Spreiter and Stahara* [1980] gasdynamic parameters with the actual solar wind conditions measured on the 2nd October 1997 to calculate the initial density (5.3 cm^{-3}) and temperature ($4.1 \times 10^6 \text{ K}$) of the magnetosheath ion population and to determine the initial (315 kms^{-1}) and final (170 kms^{-1}) V_{sheath} along our model magnetopause. We have increased V_{sheath} linearly from its original to final values. We have also included a reduction in magnetosheath density to reflect the fact that the magnetosheath portion of the reconnected field line will gradually empty itself of plasma as it is stretched across the front of the magnetopause [cf *Zwan and Wolf*, 1976]. However, for our simplified model we have kept the Alfvén speed constant at 350 kms^{-1} . We consider the reconnection site to be a field-aligned distance of $15 R_e$ above POLAR and consider field line motion along a distance of $10 R_e$ along the magnetopause. After travelling this distance, the angle θ in Figure 3 will become non-negligible, and at the density of the plasma crossing the magnetopause will be low and therefore we neglect particle entry beyond this point. Our model considers only field aligned ions, neglecting any mirrored or ionospheric populations. More sophisticated models would, however, need to take account of the effect of density and magnetic field variation on the Alfvén speed, and examine in more detail the way that V_{sheath} varies along the magnetopause.

Model Results

Figure 4 shows the output for our model based on the inputs discussed above. The plot is a similar energy spectrogram as Figure 1, 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 about

83° latitude a second higher energy dispersion can be seen with increasing energy with decreasing latitude. Densities are more than an order of magnitude higher in our model than in the observed cusp spectrogram in Figure 1 which may indicate that the *Spreiter and Stahara* model predicts too large initial sheath densities. We have, however, assumed a transmission coefficient of unity at the magnetopause which will result in an overestimate of the flux levels in the cusp.

The lower latitude dispersion in the model results, does not quantitatively match that in the POLAR data, and this may be due to several reasons. Firstly, we have assumed a constant field line convection velocity at the spacecraft's altitude in the cusp. Any real variation in convection velocity would, however, stretch, or compress parts of the dispersion in latitude. Secondly, a more sudden, reversed energy dispersion at the equatorward edge of the cusp would also be created by, for example, an exponential rather than linear increase in V_{sheath} along the magnetopause. Gasdynamic models do not, however, suggest such a sharp change in magnetosheath velocities over this distance. Thirdly, the density reduction used in our model would actually increase the Alfvén speed along the magnetopause, increasing particle acceleration and emphasising the reversed dispersion at the equatorward edge of the cusp. The Alfvén speed may also increase as reconnected field lines travelling towards the front of the magnetopause encounter greater magnetic compression at the magnetopause [*Crooker et al.*, 1982]. A more sophisticated model incorporating these effects will be the subject of future work. However, despite these quantitative discrepancies, we have demonstrated theoretically that a split V-shaped dispersion can be created from a single high latitude reconnection site if the effect of the sheath flow speed and/or Alfvén speed variation is taken into account. Reasonable variation of the model input parameters does not change the general results of the model.

Summary and Conclusions

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

We have demonstrated using a simple model simulating particle entry across the open magnetopause lying sunward of a high latitude reconnection site, that a reconnected field line which accelerates as it moves sunward into regions of lower magnetosheath flow velocity can give rise to the split dispersions observed. We note that an increasing Alfvén speed due to density reduction and/or increasing magnetic field may also augment the energy of this secondary dispersion.

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Figure 1. TIMAS H⁺ and He⁺⁺ spectrogram for 2nd October 1997.

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.

Figure 3. A velocity space plot in the Earth's rest frame and the de-Hoffman Teller frame showing field-aligned bulk flow at a rotational discontinuity at the magnetopause.

Figure 4. Model spectrogram results of cusp ion dispersions during high latitude reconnection.

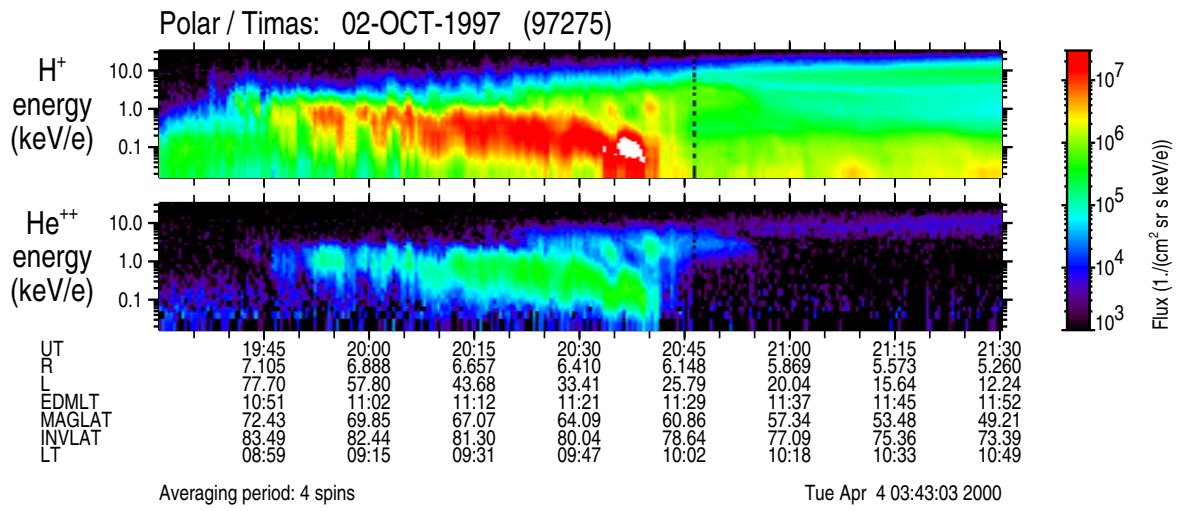


Figure 1

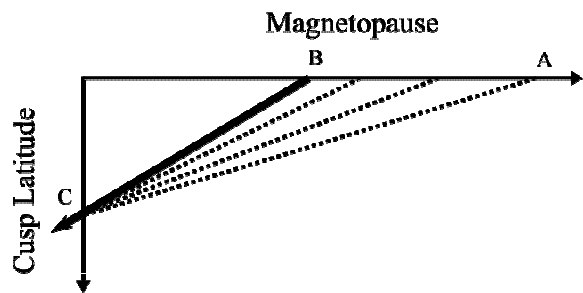


Figure 2

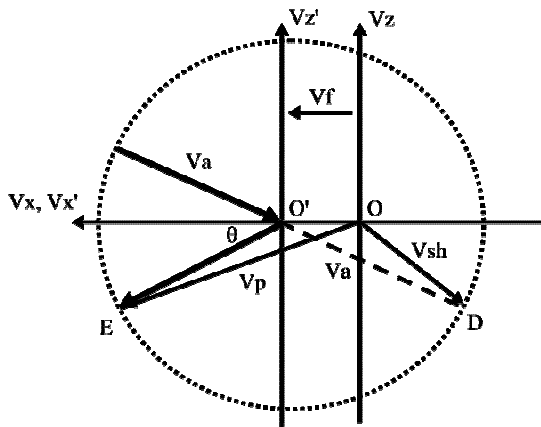


Figure 3

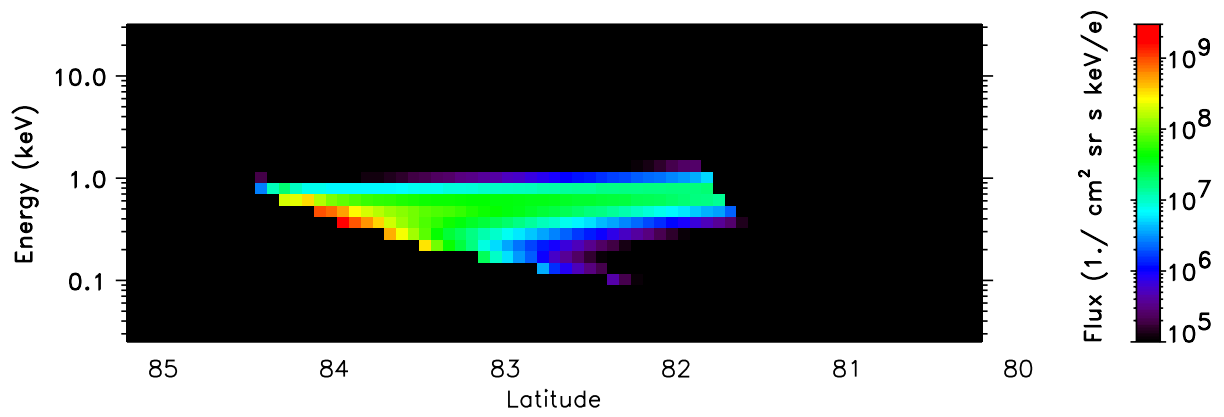


Figure 4