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The characteristics of the magnetopause reconnection X-line deduced from low-altitude satellite observations of cusp ions

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Abstract. We present an analysis of a "quasi-steady" cusp ion dispersion signature observed at low altitudes. We reconstruct the field-parallel part of the Cowley-D ion distribution function, injected into the open LLBL in the vicinity of the reconnection X-line. From this we find the field-parallel magnetosheath flow at the X-line was only 20 ± 60 km s⁻¹, placing the reconnection site close to the flow streamline which is perpendicular to the magnetosheath field. Using interplanetary data and assuming the subsolar magnetopause is in pressure balance, we derive a wealth of information about the X-line, including: the density, flow, magnetic field and Alfvén speed of the magnetosheath; the magnetic shear across the X-line; the de-Hoffman Teller speed with which field lines emerge from the X-line; the magnetospheric field; and the ion transmission factor across the magnetopause. The results indicate that some heating takes place near the X-line, and that sheath densities may be reduced in a plasma depletion layer. We also compute the reconnection rate. Despite its quasi-steady appearance on an ion spectrogram, this cusp is found to reveal a large pulse of enhanced reconnection rate.

Introduction

Recent models of cusp ion precipitation have demonstrated some important principles of how magnetosheath plasma gains access to the ionosphere along newly-opened field lines, produced by reconnection at the dayside magnetopause [Onsager et al., 1993; Lockwood and Smith, 1994]. Once the field line is open, the ions stream continuously across the magnetopause. These ions have access to the ionosphere along each newly-opened field line until it is appended to the tail lobe. The velocity filter effect [Rosenbauer et al., 1975; Hill and Reiff, 1977] arises because cusp ions of different field-aligned velocity, injected simultaneously across the magnetopause onto any one field line, have different flight times along that field line. Hence they have different arrival times in the ionosphere and, as the field line is convecting, are spatially dispersed along the locus of the field line. Figure 1 shows a typical dispersion signature for an equatorward-moving satellite for steady poleward convection and/or a steadily equatorward-eroding open/closed field line boundary [Lockwood and Smith, 1992]. The dashed lines connect ions which are injected across the magnetopause at the same place (Pₘ, which each field line reaches at a time t, after it is opened) and are given by the time-of-flight relation:

\[
d_s(m/2E)^{1/2} = t_r(t_r+t_u) = t_f(1-V_c/N_c)-t_u
\]

where \(m\) and \(E\) are the ion mass and energy, \(d_s\) is the distance along the field line from \(P_m\) to the satellite, and \(V_c\) and \(V_s\) are the convection and satellite speeds normal to the open-closed boundary, OCB (both in the OCB rest frame and both defined as positive poleward). A field line opened at a time \(t_o\) is observed at a time \(t_f\) (in fig. 1 defined as zero at the OCB where \(t_f = t_u\)) at a distance \(V_c t_o = V_c t_o\) poleward of the OCB. Ions begin to enter the magnetosphere along each newly-opened field line near the X-line, where \(t_u\) has a minimum value of \(t_u = 0\), which by equation (1) yields a minimum \(E\) called the "lower cut-off" energy, \(E_{t_u}(t_o)\). In other words, the lowest energy ions seen at any one \(t_u\) have the longest flight time and were the first to be injected (and thus were injected close to the X-line). In figure 1, \(P_i\) is at the X-line and \(E_{p_i}\) is shown as the lower part of the solid line. The dashed line labelled \(P_i\) corresponds to the energies and arrival times of ions injected at the reconnection X-line, a distance \(d_i\) from the satellite.

The theory of Cowley [1982] predicts that ions injected into the open low-latitude boundary layer (LLBL) will have a D-shaped ion velocity distribution function. This prediction has recently been verified in considerable qualitative and quantitative detail [Onsager et al., 1993; Lockwood and Smith, 1994]. Figure 1 shows a typical dispersion signature for an equatorward-moving satellite for steady poleward convection and/or a steadily equatorward-eroding open/closed field line boundary [Lockwood and Smith, 1992]. The dashed lines connect ions which are injected across the magnetopause at the same place (Pₘ, which each field line reaches at a time t, after it is opened) and are given by the time-of-flight relation:

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quantitative detail by Gosling [1990], Smith and Rodgers [1991] and Fuselier et al. [1991]. The minimum speed of these injected ions will be very close to $V_p$, the de-Hoffman Teller velocity [Smith and Rodgers, 1991]. At the X-line this has a value of $V_{pX}$, and the ions from the X-line are dispersed along the dashed line marked $P_A$ but only down to $A$, which is at the minimum injected energy of $(mV_{pX}^2/2)$ and which the satellite intersects at a time $t_A$. Lockwood and Smith [1994] have shown that, as each newly-opened field line evolves from the X-line to the tail lobe, the minimum injected energy firstly rises (as the field line accelerates) and then falls near the magnetic cusp (as it straightens). In figure 1, the minimum energy of ions injected across the magnetopause does not fall back to $(mV_{pX}^2/2)$ until the source point $P_2$. Ions from $P_2$ are dispersed along the dashed line labelled $P_2$ down to the point $B$, encountered by the satellite at time $t_B$. For $t_B < t_A$, the minimum energy ion energy, $E_{i0}$ exceeds $(mV_{pX}^2/2)$.

Figure 1 shows that at an energy $E_{i0} < (mV_{pX}^2/2)$, the equatorward-moving satellite will observe a low energy cutoff ($E_{i0} = E_{i0}$) at a time $t_A < t_B$ while at an energy $E_{i0} > (mV_{pX}^2/2)$, it will observe it at $t_A > t_B$. At an energy just greater than $(mV_{pX}^2/2)$, the satellite will observe the cut-off three times and there will be a local minimum in the ion distribution function, $f(t)$, between $t_A$ and $t_B$. This set of features is used here to estimate $t_A$ and hence $V_{pX}$.

**Observations on 26 January 1984**

We present an analysis of ion observations made by DMSP-F7 spacecraft as it traversed equatorward through the cusp on 26 January, 1984. This pass reveals a cusp plume of a type which Lockwood and Smith [1994] have pointed out reveals "quasi-steady" reconnection and which Ontager et al. [1993] have modelled using the concepts of a steady-state, open magnetosphere. Figure 2 shows the sequence of $f(t)$ during this pass, which reveals that $E_{i0}(t)$ rose with time, as in figure 1. However, ion scattering and aliasing (by changes in particle flux within the 1-s. instrument integration periods) make precise determination of $E_{i0}(t)$ from $f(t)$ difficult. To make a better estimate of $E_{i0}$ we here make use of the plots of $E_{i0}$ at constant energy, $E$ (figure 3). At all energies, a decay in $f(t)$ is seen as the satellite emerges through the equatorward edge of the cusp. A clear onset of the decay (i.e. the last high value before the major decrease in $f$) can usually be defined and, where not unambiguously clear, it can be found by reference to adjacent channels. For the higher energy channels (figure 3a), the decay occurs later for higher $E$, as expected: its onset is marked by a dot for each energy channel. Figure 3b shows the behaviour is more complex at lower energies. For $E = 100$ eV, a clear decay is observed at $t_A$ between 112s and 114s ($t_A = 0$ is here defined at a reference time of 12:44:22, not the OCB): subsequently, $f$ remains at an intermediate level before decaying gradually, which we attribute to higher-energy ions scattered to lower energies. The same sort of behaviour is seen at $E = 147$ eV, but with a small peak at $t_A = 121$ s, which is also observed at 215 eV and 314 eV. At $E = 462$ eV and above, the onset of the decay is after $t_A = 121$ s. This is exactly as predicted in figure 1, with the added complication of the scattered ions. We believe the small peak at $t_A = 121$ s is significant because it occurs in three energy channels, but also because it is located at the end of the change in the onset time of the decay from $t_A$ of 112 s to 121 s, as $E$ rises from 100 eV to 314 eV. We identify the time $t_A$ to be 121s (and $t_B$ to be in the interval 114-117s). The lowest energy showing $f$ above scattered

![Figure 2](image_url)

**Figure 2.** Sequential ion velocity distribution functions, $f(t)$, observed by DMSP-F7 during a cusp crossing on 26 January 1984 between (a) 12:46:01 and (i) 12:46:09. Isotropic downward fluxes of protons are assumed. The lower solid line gives the one count level. Solid circles give the time-of-flight cut-off defined from fig. 3.

![Figure 3](image_url)

**Figure 3.** Time series of distribution function $f(t)$ for each energy ($E$) channel: (a) 679eV - 4.47keV (top); (b) 100eV - 679eV (bottom). The time $t_A = 0$ is here defined to be 12:44.
values at the time \( t_A \) is 147 eV. Below this energy the decay in \( f \) is before \( t_p \), whereas above it the decay is after \( t_A \). The minimum in \( f \) between \( t_B \) and \( t_A \) is weak because of scatter-

\[ \text{Figure 4. The Cowley-D distribution function in the (open) LLBL close to the X-line. The open circles are the values of } f(E_0) \text{ which are obtained from the last data points before the } \]

\[ \text{decays in } f \text{, shown in figure 3 by solid circles: at these points, } \]

\[ \text{E is taken to be sufficiently close to } E_{ic} \text{ that } f = f(E_0). \text{ The } \]

\[ \text{crosses are peaks of } f(v) \text{ where that peak and the noise level are } \]

\[ \text{just one energy channel apart. The solid line is the one-count } \]

\[ \text{values at the time } t_A \text{ is 147 eV. Below this energy the decay in } \]

\[ \text{in } f \text{ is before } t_p, \text{ whereas above it the decay is after } t_A. \text{ The minimum in } f \]

\[ \text{between } t_B \text{ and } t_A \text{ is weak because of scatter-} \]

\[ \text{values for } 12:35-12:45, \text{ which allows for the estimated IMP-8 to } \]

\[ \text{magnetopause propagation delay, we obtain } X, Y \text{ and } Z \]

\[ \text{components of the IMF of } -0.78, -2.99 \text{ and } -2.21 \text{ nT, respectively.} \]

\[ \text{The solar wind had density } N_{sw} \text{ of } 11 \text{ cm}^{-3}, \text{ temperature } \]

\[ T_{sw} \text{ of } 2 \times 10^5 \text{ K and flow speed } V_{sw} \text{ of } 385 \text{ km s}^{-1}. \]

\[ V_{x} = \frac{187 + 34 \text{ km s}^{-1}}{187 + 34 \text{ km s}^{-1}} \]

\[ V_{y} = \frac{187 + 34 \text{ km s}^{-1}}{187 + 34 \text{ km s}^{-1}} \]

\[ V_{z} = \frac{187 + 34 \text{ km s}^{-1}}{187 + 34 \text{ km s}^{-1}} \]

\[ \text{Conditions at the reconnection site} \]

\[ R = \frac{(N_{i//}/N_{sw})(kT_{i//}/m + V_{x}^2/2)\text{/(cV}_{\text{sw}}^2)}{2} \]

\[ \text{where } c \text{ is the term for Newtonian pressure balance with a blunt-nose magnetosphere, which is } 0.84 \text{ at the nose, and decreases as } \cos^2 \theta \text{ [Spreiter et al., 1966]. (We here take } i, \text{ the} \]

\[ \text{angle between } V_{sw} \text{ and the magnetopause normal, to be zero because the observations are close to magnetic noon). In} \]

\[ \text{modelling all injected ions in this cusp pass, Onsager et al. \[1993\] employed solar wind values very close to those} \]

\[ \text{observed by IMP-8, but with a density which was too low by a factor 2.5, implying either that sheath densities are reduced} \]

\[ \text{in a plasma depletion layer and/or that their assumed } R \text{ of} \]

\[ \text{0.5 was too high: this could yield } R \text{ as low as 0.2, which is} \]

\[ \text{Table 1. Derived X-line parameters for ion anisotropy, } \]

\[ A = T_{i//}/T_{sw}, \text{ and magnetopause heating factor, } T_{i//}/T_{sw} \]

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Figure 5. The reconnection rate variation from $E_x(t_x)$ for assumed satellite to X-line distances, $d_x$, of 10, 14 and 18Re.

Given that this pass is in the summer hemisphere and near the solstice, we would expect the inferred location of the reconnection site to give $d_x$ near the lower end of the illustrative range employed here. Figure 5 shows that the reconnection rate is highly pulsed in this example, despite its relatively smooth (step-free) ion dispersion signature. Lockwood and Smith [1994] noted that fluctuations in the rate by a factor of as much as 2 would produce little detectable effect in the cusp ion dispersion signature, and hence predicted that even apparently "quasi-steady" dispersed cusp plumes may, in fact, be due to pulsed reconnection. Figure 5 shows this to be the case in the example presented here.

We note that the $E_x(t_x)$ profile used here to define $V_x$ is quite common in dispersed cusp plumes and hence our analysis could be used with a significant number of cusp passes.

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References


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