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Overlapping cusp ion injections: An explanation invoking magnetopause reconnection

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Abstract. An explanation of overlapping cusp ion injections is presented using the pulsating cusp model of the effects of magnetopause reconnection. It is shown that two populations of cusp ions, covering separated energy ranges, can be seen simultaneously by low- or mid-altitude satellites because of the combined effect of the acceleration and the straightening of newly-opened field lines as they evolve away from the reconnection site. Observations of such signatures, recently reported in data from the Viking and Freja satellites, are discussed in terms of pulsed and steady reconnection.

Introduction

Observations of magnetosheath-like ion populations precipitating in the cusp region have revealed that "overlapping injections" can sometimes occur. At any one time during such events, two plasma populations are detected, with an energy gap between them in which no or few ions are seen. This was first reported by *Carlson and Torbert* [1980] from rocket observations, but recently has also been detected by the Viking satellite at mid-altitudes [*Woch and Lundin*, 1991; 1992; *Yamauchi and Lundin*, 1994] and the Freja satellite in the topside ionosphere [*Norberg et al.*, 1994]. One way that such a feature could arise, discussed by *Burch et al.* [1982], is if significant numbers of heavier ions are injected along with the protons. In such cases, an ion of atomic mass a (in amu) would have the same flight time as a simultaneously-injected proton if its energy was larger by the factor a . However, the data show cases which do not maintain this fixed energy ratio and mass-resolving ion detectors show that the overlap can occur for each ion species individually [*Norberg et al.*, 1994]. Both spectrogram traces in an overlap event display both energy-latitude and energy-pitch angle dispersions, indicating that the particles are precipitating down convecting field lines. *Lockwood and Smith* [1994] suggested that some mid-altitude observations of these events were due to fully pulsed reconnection and a finite gyroradius effect. However, if this were to be the only cause, overlap events would be unlikely at low-altitudes where only ions injected with close to zero pitch angle can be detected. Hence this does not explain the low-altitude Freja observations recently reported by *Norberg et al.* [1994].

Lockwood and Smith [1992; 1993; 1994] and *Onsager* [1994] have stressed that zero pitch-angle ions with different energies, seen simultaneously inside the magnetosphere/iono-

sphere on a convecting field line, must have been injected across different points of the magnetopause. This is because different energy ions have different flight times from the magnetopause to the satellite. The spectrum seen at any one time (and thus on one field line) is an ensemble: ions of low energy are injected earlier and the field line moves before the higher energy ions enter. A key point about the overlapping events is that they reveal two regions of the magnetopause where ions enter the magnetosphere and reach the satellite, separated by a region where ions either do not cross the magnetopause or, if they do, they fail to reach the satellite.

There is much evidence that cusp particles enter the magnetosphere along newly-opened field lines produced by reconnection in the dayside magnetopause [see review by *Lockwood and Smith*, 1994]. However, it is not obvious how this can produce the overlapping signatures. The problem is that once a field line is opened, ions stream continuously across the boundary. It is difficult to devise a scenario in which a field line is opened, closed and then opened again as it convects. In this paper, however, it is shown that it is not necessary to modulate the particle entry in this fashion. Overlapping signatures can arise for the continuous particle entry predicted by the reconnection model, because of the variation of the ion acceleration on crossing the magnetopause, combined with the ion time-of-flight effects.

Ion entry and acceleration predicted by the reconnection model

Figure 1 shows the dayside magnetosphere in the open magnetosphere model, for southward IMF conditions. A newly-opened field line is shown in four positions (labelled 1-4) as it evolves away from the reconnection site, X , under the influence of the magnetic curvature force ("tension") and the magnetosheath flow. The points P_n are where the field line (in position n) threads the magnetopause. Each and every newly-opened field line executes this sequence. A satellite S at low altitudes is shown observing a field line in position 4, where it sees a range of ion energies with the most energetic coming from P_3 and the least energetic coming from P_1 , near the X -line. At all P_n , ions stream across the magnetopause, as confirmed by stress-balance tests applied to both the dayside and the near-Earth tail boundaries [see *Lockwood and Smith*, 1994]. To get an overlapping signature, S must see ions from around P_3 and P_1 but not from around P_2 .

Figure 2a shows the general situation at the rotational discontinuity formed by the newly-opened field lines at a point P_n . In the ZX plane shown, the field line makes angles ϕ and θ with the magnetopause on its magnetosheath and magnetospheric sides, respectively. These angles increase with the distance from X to P_n , as the field line straightens. *Cowley* [1982] derived a theory to predict D-shaped distribu-

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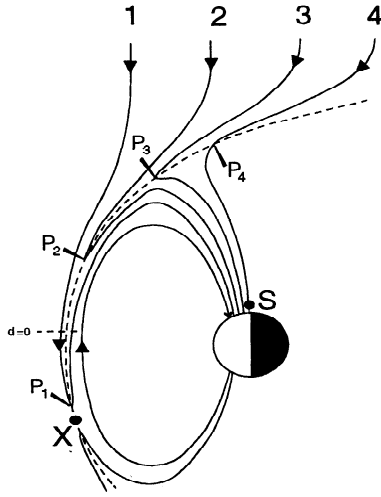


Figure 1. A schematic of the evolution of a newly-opened field line away from a low-latitude reconnection site X.

tion functions of ions injected and accelerated across the boundary by flowing along such newly-opened field lines. These predictions have recently been verified in considerable quantitative and qualitative detail [Smith and Rodgers, 1991; Fuselier et al., 1991] and were made using constructions like that shown in Figure 2b. This is a velocity space plot in the Earth's frame (V_x, V_z) and in the de-Hoffman Teller (V_x, V_z) frame (hereafter referred to as the dHT frame). The dHT frame moves with the field line at velocity V_f (in the Earth's frame) in the +Z direction such that in it there is no electric field and hence ion energy is conserved on crossing the boundary. For the simplified symmetric case employed here, in which the Alfvén speed V_A is the same on both sides of the boundary, the only bulk ion motion in the dHT frame is field-aligned at the constant speed V_A : sheath ions approaching the magnetopause have $V_x < 0$ and $V_z < 0$ (s in Figure 2b), but once injected they have $V_x < 0$ but $V_z > 0$ (i in Figure 2b). About this bulk flow is the thermal spread and only ions with $V_x < 0$ will cross the magnetopause: the minimum injected field-aligned velocity in the dHT frame is zero and Figure 2b shows that this gives a minimum field-aligned velocity of $V_f \cos \theta$ in the Earth's frame. The field-aligned bulk flow in the Earth's frame is $V_p = (V_f \cos \theta + V_A)$.

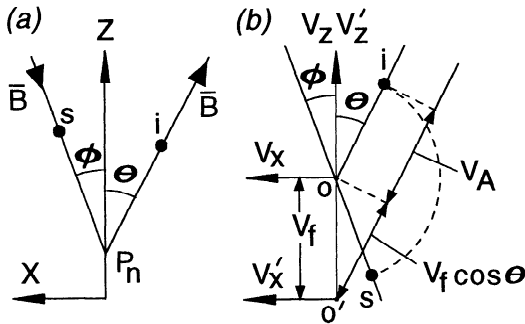


Figure 2. (a) The rotational discontinuity (RD) formed by a newly-opened field line at P_n which evolves along the magnetopause in the Z direction at speed V_f in the Earth's frame of reference. The X direction is the outward normal to the boundary. (b) A velocity space plot showing field-aligned bulk flow at the Alfvén speed, V_A , in the de-Hoffman Teller frame (V_x, V_z with origin at O) both into the RD in the magnetosheath (at s) and away from the RD in the magnetosphere (at i). This geometric construction allows the calculation of the minimum and bulk flow field-aligned speed of injected particles in the Earth's frame (V_x', V_z' with origin at O'). (Adapted from Cowley, [1982]).

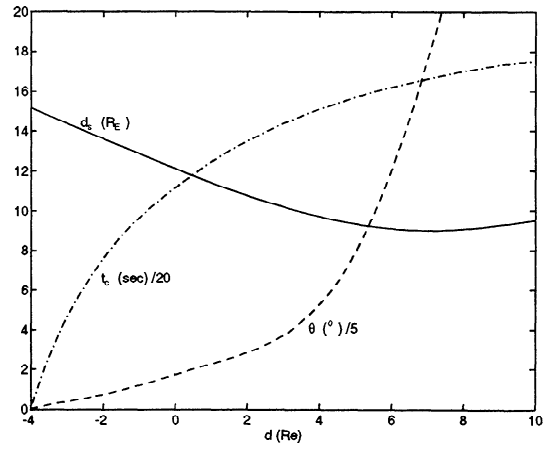


Figure 3. Variations of assumed model inputs with distance d from the nose of the magnetosphere for an X-line at $d = -4R_E$. The solid line is the distance d_s from the injection point P_n to the satellite (in units of R_E) and the dashed line is the angle $\theta/5$, where θ is in degrees and is defined by Figure 2a. The dot-dash line is $t_c/20$, where t_c is the time (in seconds) for the field line to convect from the X line to P_n and is derived by the model.

Cowley and Owen [1989] have noted that V_f is such that V_{sh} , the X component of the sheath flow which is tangential and adjacent to the boundary and in the Earth's frame, results in the field-aligned inflow speed in the dHT frame being V_A , so

$$V_f = V_{sh} + V_A \cos \phi. \quad (1)$$

Thus there is a minimum field-aligned energy of the population of injected ions (of mass m) of

$$E_{min} = m(V_f \cos \theta)^2/2 = m([V_{sh} + V_A \cos \phi] \cos \theta)^2/2 \quad (2)$$

Lockwood and Smith [1994] pointed out that E_{min} firstly rises as the field line accelerates away from the X-line (V_f increases), but then falls to zero as θ increases to 90° .

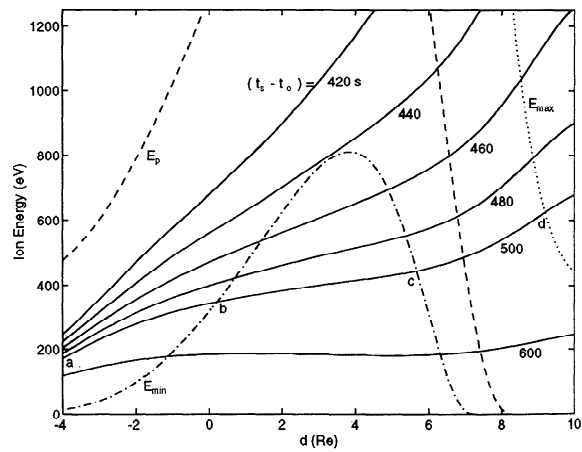


Figure 4. The ion energy, E_n , received from the magnetopause point P_n , as a function of d , the distance of P_n along the magnetopause from the nose of the magnetosphere, for various elapsed times since reconnection ($t_s - t_o$). The dot-dash, dashed and dotted lines are, respectively, the minimum energy (E_{min}), the energy of peak distribution function (E_p) and the peak detected energy (E_{max}) injected at P_n .

An explanation of overlapping injections

If at time t_s , we are observing a field line opened at a time t_o and which took a time t_c to evolve from X to an injection point P_n , then the ion time of flight from that P_n to S is

$$t_s - (t_o + t_c) = d_s / (2E_n/m)^{1/2} \quad (3)$$

where d_s is the field-aligned distance from the point P_n to the satellite S and E_n is the only energy of field-aligned ions which S can detect from the point P_n at that t_s .

The argument used here is that, as the minimum injected ion energy of the Cowley D distribution rises and then falls, there can be a range of points P_n on the magnetopause for which this minimum energy is larger than the only energy which could be seen by S (i.e. $E_{min} > E_n$), even though lower energies (from closer to the X-line) and higher energies (from closer to the satellite) are both seen. This therefore gives the overlapping injection signature at any one observation time t_s . That this can occur is demonstrated here by a simple model calculation. To make the effect clearer, the reconnection X-line is beyond the magnetosheath stagnation region at the nose of the magnetosphere. As in Cowley and Owen [1989], magnetic effects on the sheath flow are neglected so that the tangential sheath velocity V_{th} can be taken from a gas-dynamic model [Sprieter *et al.*, 1966] as a function of the distance d from the nose of the magnetosphere (which is taken to be at a stand-off distance of $10R_E$). The X line is placed at $d = -4R_E$ (i.e., $4R_E$ beyond the nose) and, for simplicity, we employ a highly draped sheath field such that V_A and $\cos\phi$ are independent of d and equal to 250 km s^{-1} and 1, respectively; assumed variations with d of the distance d_s and the angle θ are inputs to the model, given by the solid and dashed lines in Figure 3. From equation (1) we can then compute the field line velocity V_f at all d and hence the time t_c as a function of d : the result is shown by the dot-dash line in Figure 3. Equation (3) gives the variations of E_n with d , shown as solid lines in Figure 4 for field lines of various elapsed-time since reconnection, $(t_s - t_o)$. Also shown is: the variation of E_{min} (dot-dash line), calculated using equation (2); the energy of the distribution function peak, E_p , corresponding to the field-aligned ion speed V_p (dashed line); and the peak detectable energy, E_{max} (dotted line). E_{max} depends on the instrument sensitivity and the magnetosheath densities, and is here crudely estimated by saying the detector can see distribution function $f(v)$ for v up to $(V_p + 500) \text{ km s}^{-1}$. It can be seen that for $(t_s - t_o) > 440 \text{ s}$ there are points on the magnetopause for which $E_{min} > E_n$ and so they contribute no ions to the spectrum seen by S at that t_s . For example, at $(t_s - t_o) = 500 \text{ s}$ ions will be seen on the segments ab and cd of the relevant $E_n(d)$ curve in Figure 4, but not on bc for which $E_n < E_{min}$. Hence there is an energy range for which no ions are seen by S. This gap is largest for the $(t_s - t_o) = 460 \text{ s}$ case, but drops to zero width for $(t_s - t_o) = 600 \text{ s}$. Thus it is possible for two magnetopause injection regions to contribute ions to the spectrum seen at any one time, separated by a region which does not (even though the injection takes place at all points of the magnetopause). Figure 5 is a schematic of two over-lapping events such that at $t_s = t_1$ the satellite sees a field line which has an elapsed time since reconnection of $(t_s - t_o) = 500 \text{ s}$: the points a-d are marked. The evolution of these points with t_s is discussed in the following section.

Explaining observed overlapping injections using pulsed and steady reconnection

Norberg *et al.* [1994] argue that only downward cusp ion steps can be produced by pulsed reconnection and, indeed, the papers they cite do only deal with such cases. However, Lockwood and Smith [1994] have shown that the nature of the step depends on the ratio of the components of the satellite motion and convection (V_s and V_c , respectively) which are normal to, and away from, the open/closed field line separatrix. In particular, they demonstrate that if $0 < V_s < V_c$, the most common signature of pulsed reconnection will be downward ramps of ion energy with time, interrupted by upward steps, of the type presented by Norberg *et al.* This situation will often prevail for satellites like Viking, which follow a meridian at mid-altitudes, and for satellites like Freja, which move longitudinally at low altitudes (making the component V_s small). Effectively, what happens is that the elapsed time since reconnection $(t_s - t_o)$ increases within each patch of newly-opened flux as it ages, so that the E_n for all P_n fall. However, the next patch of newly-opened flux (produced by the subsequent reconnection pulse) can be convected over the satellite (because $V_s < V_c$), giving a sudden fall in $(t_s - t_o)$ and a rise in E_n for all P_n . On the other hand, low-altitude satellites moving meridionally poleward see only downward cusp ion steps because $V_s \gg V_c$.

Lockwood and Smith [1994] point out that an overlapping injection feature can be seen by a mid-altitude satellite about an upward cusp ion step, provided the reconnection only takes place in pulses, with zero reconnection rate between them. This is a finite ion gyro-radius effect and can be identified because the overlap will be present for larger pitch angle ions but downward-precipitating, field-aligned ions will only show the upward step with no overlap. Careful inspection of some of the cases reported from the Viking data reveals that they exactly fit this prediction. For example, in the lower panel of Figure 2 of Yamauchi and Lundin [1994] field-aligned ions are only seen at one energy at a time and that this energy steps up from the first to the second trace around 13:54:30. This is powerful evidence that the reconnection rate fell to zero between two pulses.

The mechanism presented in the previous section will generate overlapping signatures in ions of all pitch angles,

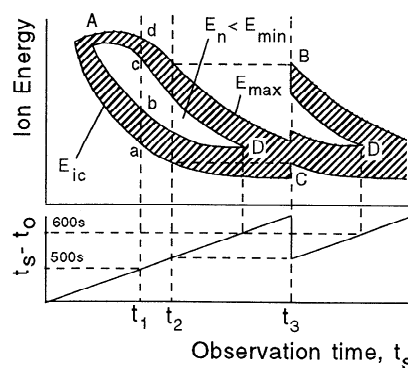


Figure 5. Schematic of two types of possible overlapping ion events, showing contours of the minimum detectable flux, such that cusp ions are only seen in the shaded regions. The reconnection is steady, except for a period of zero rate causing the upward step at $t_s = t_2$; the lower panel gives the variation of the time elapsed since reconnection $(t_s - t_o)$. The points a-d and A-D are defined in the text with reference to Figure 4.

including field-aligned. However, we also need to explain the observed sequences of cusp ion spectra with t_s . For $t_s < t_3$ in Figure 5 the reconnection is steady, so the poleward-moving satellite observes field lines of increasing $(t_s - t_o)$ with time t , and the minimum observed energy falls continuously (this time-of-flight cut-off energy was referred to by Lockwood and Smith [1992; 1994] as E_{ic} and is E_n for the X line). For the case shown in Figure 4, a clear overlapping signature will be seen after $(t_s - t_o)$ reaches 440s, when the distribution function $f(E)$ goes to zero at 800 eV (because E_n falls below E_{min}). In fact, consideration of the full Cowley-D distribution injected at each P_n predicts a deepening minimum in $f(E)$, descending in energy, will have been observed before this as $(t_s - t_o)$ increases from about 410 to 440s. Thus the onset of the overlap would appear as a bifurcation of the pre-existing cusp signature (A in Figure 5). Some observed examples could be interpreted as forming via such a bifurcation (for example, shortly after 00:53 in Figure 3 of Woch and Lundin [1991] is one possibility) and can thus be explained by steady reconnection and steady magnetosheath conditions. As discussed earlier, the width of the null reduces to zero at about 180 eV when $(t_s - t_o)$ increases to about 600s. This steady-state case can thus predict the observed amalgamation of the two overlapping traces at low energies (the points D in Figure 5) [e.g. Figure 1 of Norberg *et al.*, 1994].

In many other cases, however, (for example at 08:40:30 in Figure 7 of Lundin and Woch [1991] and 20:26:15 in Figure 1 of Norberg *et al.*, [1994]) the higher energy, overlapping trace is, even at onset, detached in energy from the lower-energy trace. This is not consistent with the bifurcation at A in Figure 5, but more like the onset B. There are two ways in which this could come about, both involving departures from steady state. In the first, there could be pulsed reconnection with $V_c > V_n$, such that an upward cusp ion step is formed. This occurs in Figure 5 at $t_s = t_3$ when $(t_s - t_o)$ discontinuously steps back to its value at t_2 , giving an onset of a detached overlapping trace at B. However, the lower trace would also show an upward step, including a step in E_{ic} , at C. This can be seen shortly after 00:53 in Figure 3 of Woch and Lundin [1991], but is not a general feature of the reported examples. Indeed, there are several cases of a detached onset of the upper trace, with no apparent step in the dispersion of the lower trace (i.e. B without C) [e.g. Figure 1 of Norberg *et al.*, 1994; Figure 7 of Woch and Lundin, 1991]. These therefore appear to be cases where the reconnection rate is relatively steady (meaning that rate variations are smaller than a factor of about 2 [Lockwood and Smith, 1994, Lockwood *et al.*, 1994]) at a static X-line. In such cases, the appearance of the overlapping signature could be explained by a rapid fall in the magnetopause Alfvén speed (caused by a fall in the magnetic field and/or a rise in the plasma density). This would cause a fall in the field line speed V_f and in the ion acceleration on crossing the magnetopause with reconnection time t_o . Thus E_{min} , E_p and E_{max} would all rise suddenly for all P_n with increasing $(t_s - t_o)$. As the satellite observed field lines of higher $(t_s - t_o)$, the sudden onset of an overlap (but with no step in E_{ic}) could be seen as it moved onto earlier-reconnected (smaller t_o) field lines for which the acceleration was higher. Several events appear to fall into this class and quasi-steady reconnection and magnetosheath changes may be a common cause.

It has been shown here that the continuous entry of magnetosheath ions, along newly-opened field lines produced by magnetopause reconnection, can give rise to "overlapping

injection" signatures of cusp ions due to the acceleration and straightening of the field lines. The model calculations presented will not match all such observations in all details, due to the simplifying assumptions made. The model also provides an explanation of why overlapping signatures are not always seen. This is because E_{min} may never exceed E_n , for example if d_s is large because the magnetosphere is less compressed because the solar wind dynamic pressure is low.

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