GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L07108, doi:10.1029/2005GL025598, 2006

Temporal evolution of a staircase ion signature observed by Cluster in the mid-altitude polar cusp

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Received 23 December 2005; revised 15 February 2006; accepted 10 March 2006; published 12 April 2006.

[1] We use the Cluster string of pearls configuration to investigate temporal variations of ion precipitation in the mid-altitude polar cusp. On 7 Aug. 2004, Cluster 4 was moving poleward through the Northern cusp, followed by Cluster 1, Cluster 2, and finally Cluster 3. The Wind spacecraft detected a Southward turning of the Interplanetary Magnetic Field (IMF) at the beginning of the cusp crossings and IMF-Bz stayed negative throughout. Cluster 4 observed a high energy step in the ion dispersion around 1 keV on the equatorward side of the cusp. C1, entering the cusp around 1 minute later, did not observe the high energy step anymore but a partial dispersion with a low energy cut-off reaching 100 eV. About 9 min later, C3 entered the cusp and observed a full ion dispersion from a few keV down to around 50 eV. The open-closed boundary, identified by electron precipitation, was initially moving equatorward at a rate of -0.43° ILAT/minute at the beginning of the event and then slowed down to -0.16° ILAT/minute, suggesting the erosion of the dayside magnetosphere under IMF Southward. This event is explained by the onset of dayside reconnection when the IMF turned southward; the step being the first signature of the reconnection that would then evolve as a full dispersion as reconnection goes on. We observed 1–3 keV ions near the open-closed boundary on the three spacecraft crossings that suggests a continuous reconnection during about 9 minutes. **Citation:** Escoubet, C. P., et al. (2006), Temporal evolution of a staircase ion signature observed by Cluster in the mid-altitude polar cusp, *Geophys. Res. Lett.*, *33*, L07108, doi:10.1029/2005GL025598.

1. Introduction

[2] Since the first observations of FTEs in the polar ionosphere [*Goertz et al.*, 1985], the question of quasi-continuous versus intermittent reconnection in the cusp has been the subject of a long debate which is still taking place. At the beginning, this debate was mainly driven by the different means used to observe the polar cusp. Low altitude spacecraft cross the cusp rather quickly and thus generally observe signatures of quasi-continuous reconnection, while ground-based radars and photometers that can observe the cusp for a few hours would usually observe signature of bursty reconnection. However at the end of the 80s low altitude spacecraft had observed a few examples of bursty reconnection or FTEs. [*Basinska et al.*, 1989] presented one event where the electric field data could well be fitted by the FTE model developed by [*Southwood*, 1987]. *Lockwood and Smith* [1989] showed that the cusp observed by DE-2 could be well explained by an FTE.

[3] The typical signature of reconnection in the polar cusp is the smooth change of the energy of the precipitating ions, also called dispersion, observed as a spacecraft is crossing the cusp. This signature is due to the velocity filter effect produced by the motion of the newly reconnected field lines away from the reconnection point. The high energy ions from the magnetosheath that enter the cusp will then be observed close to the first open field line, while the low energy ones, which take a longer time to reach the ionosphere, will be detected further away from it [*Reiff et al.*, 1977]. In principle, the ion dispersion can also be used to tell if the reconnection process is quasi-continuous or intermittent: a continuous reconnection will produce a smooth energy dispersion while an intermittent reconnection will produce steps in the dispersion [*Lockwood and Smith*, 1992].

[4] *Newell and Meng* [1991] reported the first observations of ion energy steps. They were found in about 10% of the DMSP cusp crossings but were explained by the acceleration process in the reconnection region and not by intermittent reconnection. On the other hand, *Escoubet et al.* [1992] presented an event where the ion dispersion was presenting three distinct energy steps which were explained by the crossing of three successive FTEs, in agreement with the model developed by *Cowley et al.* [1991]. *Lockwood and Smith* [1992, 1994] showed that the low-energy ion cut-off can give the history of the reconnection rate; a burst of reconnection is characterized by constant energy cut-off (step) and a period with no reconnection by a jump in the cut-off. This was applied to a DMSP pass and showed that three bursts of reconnection, with the reconnection rate going to zero in between, could explain the observations. On the other hand, *Newell and Meng* [1995], using 21 DMSP crossings, showed that the reconnection would rarely stop completely for more than one minute. Later, *Lockwood et al.* [1998] demonstrated that the precipitating and mirroring ions can be well modeled by a series of

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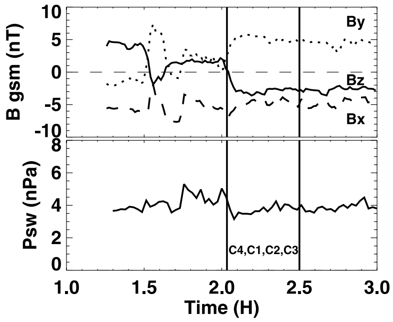

Figure 1. Solar wind conditions on 7 Aug. 2004 from the Wind spacecraft. A shift of 75 min was applied to the data to take into account the propagation from Wind position to the front of the magnetosphere. Bx is plotted with a dashed line, By a dotted line and Bz a solid line.

reconnection pulses lasting 0.5–2.5 min. separated with 1–3 min of slow reconnection.

[5] Quasi-continuous reconnection was again put forward with the first observations of the polar cusp by two spacecraft quasi-simultaneously. First, *Onsager et al.* [1995] showed an event with DE-1 and DE-2 crossing the cusp with a 20 min interval and presenting both a discontinuity in the ion dispersion at about the same invariant latitude. *Trattner et al.* [1999] showed very similar structures in the ion dispersion observed by Polar and Interball, separated by 1.5 h in time. Later on, *Trattner et al.* [2002] used a conjunction between Polar and FAST to demonstrate that the four steps observed by both spacecraft were spatial and not temporal since Polar spent about 30 min. in the cusp while FAST spent only 3 min.

[6] This study will present the observation of an ion step and its evolution in time as it was crossed by the four spacecraft successively. The first part will present the solar wind conditions and the Cluster position during the cusp crossing on 7 Aug. 2004. In a second section the ion and electron data from the four spacecraft will be presented. Finally in the third section we will discuss the results in terms of new injection in the polar cusp.

2. Observations

2.1. Interplanetary Conditions and Cluster Orbit

[7] The magnetic field and solar wind dynamic pressure from the Wind spacecraft on 7 Aug. 2004 are presented on Figure 1. Before the Cluster cusp crossing at around 02 UT, the IMF was Northward and decreasing, the By component switched from negative to positive and Bx was fairly constant around −5 nT. At around the time of the cusp entry by C4, Bz turned Southward then stayed constant around −2 nT, By increased from 2 to 5 nT, giving an IMF clock angle around 120°, and Bx stayed around −5 nT. The solar wind pressure was higher than usual at around 5 nPa and then dropped to 4.5 nPa at the beginning of the cusp crossings. The four Cluster spacecraft crossed the polar cusp at an altitude of 4.5 R_E between 02 and 03 UT. The spacecraft were following each other with C4 leading, with C1 following 4 min later, C2, 9 min later and finally C3, 18 min later (as we will see below, the differences in time at the cusp entry are about half of these times since the cusp was moving equatorward and the spacecraft poleward). The spacecraft were exactly on the same meridian plane at around 12.5 h MLT.

2.2. Cluster Observations

[8] The ion and electron precipitations observed by the four Cluster spacecraft in the polar cusp are shown on Figure 2. At the beginning the spacecraft were in the dayside plasmasheet, characterised by ions and electrons of energy above 10 keV, then C4 crossed the open-closed boundary (OCB) at 02:02:06 UT (dashed line on Figure 2) and entered the cusp. A few minutes later, C1 crossed the OCB at 02:03:02 UT, followed by C2 at 02:06:00 UT and C3 at 02:10:40 UT. The cusp is characterised by high flux of ions in the range 50 eV–3 keV and an increase of electron flux below a few 100s eV. The start of the electron precipitation (OCB) is detected equatorward of the ion precipitation due to the shorter time of flight and poleward drift of the electrons, similar to the electron edge observed at the magnetopause [*Gosling et al.*, 1990]. Using the OCB crossing times by each of the four spacecraft and knowing the position of each spacecraft in invariant latitude we can estimate the average motion of the OCB between two spacecraft crossings. We found that the OCB was moving equatorward and its speed was initially −0.43° ILAT/min between C4 and C1, and then −0.16° ILAT/min between C1 and C2 and between C2 and C3.

[9] An ion step around 1 keV is observed by C4 around 02:06 UT (marked (1) on Figure 2a). This step is defined by the sudden drop of the low energy cut-off of the ions on the

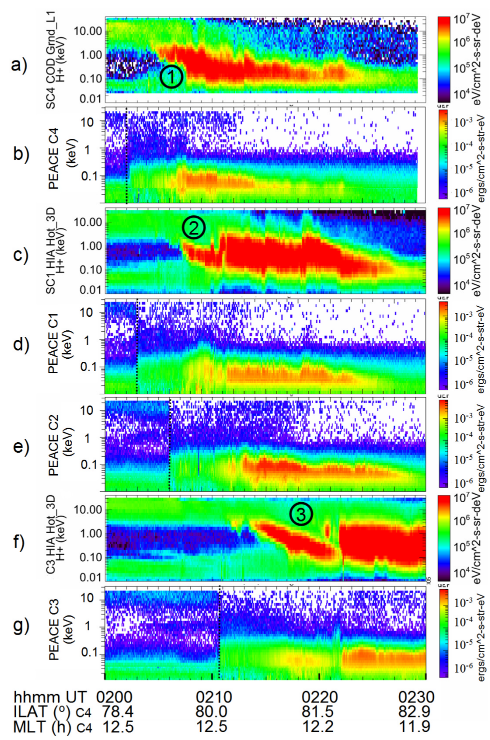

Figure 2. Omnidirectional ion and downgoing electron spectrograms on (a and b) C4, (c and d) C1, (e) C2, and (f and g) C3. Open-Closed Boundary is indicated by the dotted line on the electron spectrograms. The ion energy steps and dispersions are marked from 1 to 3.

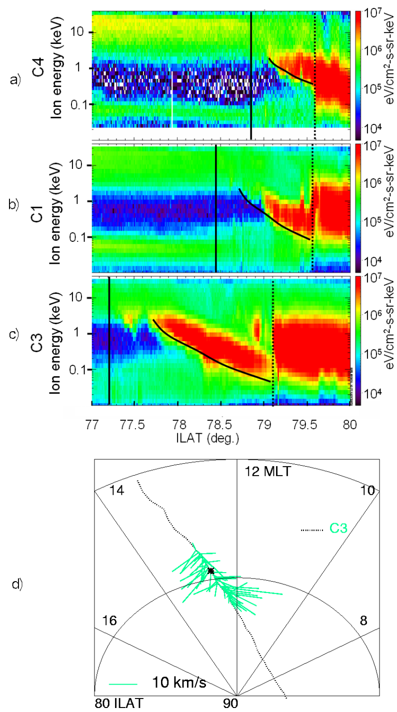

Figure 3. Omnidirectionnal ion spectrograms as a function of invariant latitude for (a) C4, (b) C1 and (c) C3. OCB is marked by a solid vertical line and the boundary between the energy steps/dispersion and the main cusp is marked by a dotted line. The solid lines mark the low-energy cut-off. (d) Flow speed from C3 in ILAT-MLT diagram. The star marks the boundary between the dispersion on the equatorward side of the cusp and the rest of the cusp poleward.

poleward side. About 1 min later, C1 observed a step of around 400 eV (Figure 2c), clearly visible in the high energy cut-off. Finally, C3 observed a complete ion dispersion 9 min later (Figure 2f). The electron precipitation shows relatively low flux around 100 eV (typical cusp energy) where the ion step and dispersion are observed (02:02–02:07 on C4, 02:03–02:11 on C1, 02:06–02:13 on C2 and 02:11–02:22 on C3) together with some low electron flux around 1 keV. Poleward of the step, in the centre of the cusp, the 1 keV electrons disappeared and the flux of electron below 100 eV increased significantly.

[10] To facilitate an easy comparison of the ion steps we have plotted the 3 spacecraft ion spectrograms as a function of invariant latitude (Figure 3). We can clearly see the motion of the OCB (solid vertical line) to lower latitude between C4, C1 and C3. The boundary between the energy steps/dispersion and the main cusp (dotted vertical line) is also moving equatorward, but at a slower rate (−0.03° ILAT/min) than the OCB. The energy step observed at C4 (panel a) shows a decreasing low energy cut-off (curved line) within the step, decreasing from 2 keV down to 300 eV. The width of the step in latitude is about 0.5° ILAT. C1 (panel b) observed a longer step than C4, the low energy cut-off starting from 2 keV and reaching 100 eV. The size of the step is now around 0.8° ILAT. C3, on the other hand, observed a complete dispersion, starting with a low energy cut-off at about 2 KeV and decreasing down to 60 eV. Now the dispersion is about 1.4° ILAT. In addition, a burst of ions around 3 KeV is observed equatorward of the dispersion at about 77.5° ILAT. Looking at the detailed distribution function (not shown), the distribution is the same as the one observed at the beginning of the dispersion (around 77.7° ILAT) which is an indication that the OCB may have moved quickly poleward and then equatorward again, producing a gap in the precipitation of the ions.

[11] The ion flow measured by C3, perpendicular to the magnetic field, is shown on Figure 3d. The flow was eastward and poleward where the ion dispersion is observed on C3 (below 79 deg. ILAT) and westward and poleward in the main cusp poleward of the dispersion. The same convection pattern is observed on C4 and C1 (not shown).

3. Discussion and Conclusion

[12] The consecutive cusp crossings of the four Cluster spacecraft allow us to observe the changes occurring in the polar cusp on 7 August 2004. These crossings occurred just after a southward turning of the IMF. A clear erosion of the magnetosphere is observed with the motion of the OCB equatorward, the rate of which was higher between the first two spacecraft (−0.43° ILAT/min) as compared to the last two spacecraft (−0.16° ILAT/min). These values are consistent with previous studies, which recorded a shift of the cusp equatorward in the range −0.2–0.3° ILAT/min [*Sandholt et al.*, 1994] after a southward turning of the IMF. We find that the initial shift of the cusp is faster in the first minute than afterward. This may result from the fact that the reconnection rate is higher at the onset of reconnection and then slows down with time.

[13] The first spacecraft (C4) to enter the cusp observed an energy step with a decreasing low-energy cut-off from 2 keV to 300 eV and a width around 0.5° ILAT. The second spacecraft (C1), 1 min. later, observed a wider step or a partial dispersion, around 0.8° ILAT, with the low energy cut-off decreasing from 2 keV down to 100 eV. Finally C3, 9 min. later, observed a full dispersion extending over 1.5° ILAT and with a low energy cut-off from 2 keV down to 50 eV.

[14] We will now show that the energy steps can be explained by the onset of plasma injection at the dayside magnetopause after the southward turning of the IMF. A sketch of the injection development is shown on Figure 4. For simplicity we indicate only three ion energies but the figure is representative of the whole energy range. Let us assume that the injection started at t_1 at the dayside magnetopause, coinciding with the southward turning of the IMF. At t_2, C4 observed the first high energy ions arriving from the source, then at t_3, C1 observed a step or incomplete dispersion where low energy ions did not arrive yet and finally at t_4, C3 observed the full dispersion. The fact that we observe the high energy ions on the three spacecraft crossings, near the OCB, suggests that the injection was continuing between the first and the last spacecraft crossing, a total time of about 9 minutes.

[15] Ion energy steps were associated in the past with acceleration of ions by the reconnection process [*Newell and Meng*, 1991] or alternatively by pulsed reconnection [*Escoubet et al.*, 1992; *Lockwood and Smith*, 1992]. In our study we observe a step in energy a few minutes after the

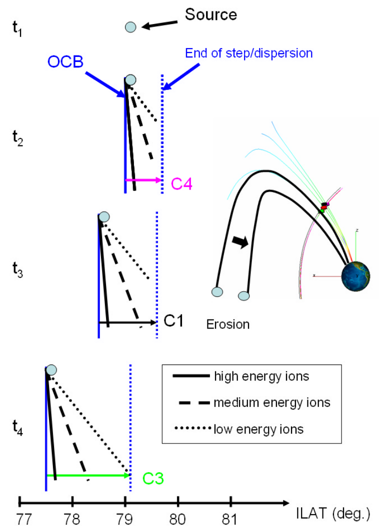

Figure 4. Sketch of the start of the injection and the subsequent observation by C4, C1 and C3.

rotation of the IMF southward. We believe that the start of a new injection on the dayside magnetopause created the step. This reconnection continues, also producing erosion of the dayside magnetosphere, and the ion dispersion grows in size to finally reach a well developed dispersion after 9 minutes.

[16] If reconnection on the dayside of the magnetosphere can explain the step and the dispersion on the equatorward side of the cusp, the centre of the cusp at higher latitude (above 79° on C3) seems to be populated by another source. First of all, because the ion and electron flux as well as the ion density (not shown) are higher in the centre of the cusp than in the step/dispersion. Secondly the flow is westward in the centre of the cusp while it is eastward in the step/dispersion. This westward flow seems to indicate that the injection in the centre of the cusp is taking place on the northern dusk flank, consistent with anti-parallel reconnection with $By > |Bz|$ and negative Bz [*Crooker*, 1979]. The field lines after reconnection would move westward and poleward. On the other hand the eastward flow on the step/dispersion suggests that reconnection is taking place on the dayside magnetosphere. We would therefore have two sources, one on the dayside of the magnetosphere which may be produced by component reconnection or alternatively by reconnection in the southern hemisphere and one in the northern dusk flank produced by antiparallel reconnection.

[17] This is in agreement with the "double cusp" model developed by *Wing et al.* [2001] and further discussed by *Sandholt et al.* [2003]. In addition, *Sandholt and Farrugia* [2003] observed a "midday gap aurora", attributed to component reconnection near the subsolar point, simultaneously with strong aurora brightening in the afternoon sector produced by anti-parallel reconnection in the high-latitude postnoon sector. The fairly low flux of electrons observed here on the equatorward side of the cusp could produce the aurora gap and the stronger electron precipitation in the main cusp could produce the enhanced brightening.

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