STAIRCASE ION SIGNATURE OBSERVED BY CLUSTER IN THE MID-ALTITUDE POLAR CUSP

C. P. Escoubet[1], J. M. Bosqued[2], J. Berchem[3], M. G. G. T. Taylor[1], F. Pitout[4], H. Laakso[1], A. Masson[1], M. Dunlop[5], H. Reme[2], I. Dandouras[2] , A. Fazakerley[6]

[1] *ESA, ESTEC, The Netherlands*
[2] *CESR, Toulouse, France*
[3] *UCLA/IGPP, USA*
[4] *MPI for Extraterrestrische Physik, Garching, Germany*
[5] *RAL, Oxford, United Kingdom*
[6] *MSSL, UCL, United Kingdom*

ABSTRACT

We use the Cluster string of pearl configuration in the mid-altitude polar cusp to investigate temporal variations of ion precipitation in the polar cusp. On 7 Aug. 2004, Cluster 4 was moving poleward through the Northern cusp, followed by Cluster 1 about 3 min. later, Cluster 2 about 9 min. later and finally Cluster 3 about 18 min. later. The ACE spacecraft detected a Southward IMF turning before the cusp crossings and IMF-Bz stayed negative throughout. Cluster 4 observed a staircase ion dispersion with 2 steps, a high energy one around 1 keV at low latitude and a low energy one at higher latitude. C1 around 3 min. later did not observe the high energy step anymore but a partial dispersion with a low energy cut-off reaching 100 eV. About 18 min. later, C3 observed a full ion dispersion from a few keV down to around 50 eV. This event is discussed in terms of temporal evolution of newly reconnected field lines on the equatorward side of the cusp for southward IMF.

1. INTRODUCTION

Since the first observations of flux transfer events (FTEs) in the polar ionosphere by Goertz et al. [1] quasi-continuous versus intermittent reconnection in the cusp has been the subject of a long debate. Originally, this debate was mainly driven by the different means used to observe the polar cusp. Low-altitude spacecraft that cross the cusp rather quickly generally would observe signatures of quasi-continuous reconnection while ground-based radars and photometers that can observe the cusp for a few hours would usually observe signatures of bursty reconnection. However, by the end of the 80s, a few bursty reconnection events or FTEs were observed by low-altitude spacecraft. Basinska et al. [2] presented one event for which the electric field data were consistent with Southwood's FTE model [3]. Lockwood and Smith [4] showed that low altitude signatures of the cusp observed by DE-2 could be well explained by FTEs.

The typical signature of reconnection in the polar cusp is the smooth change in energy of the precipitating ions, called dispersion, which is observed as a spacecraft is crossing the cusp. This signature is due to the velocity filter effect produced by the motion of newly reconnected field lines moving away from the reconnection site. High energy ions from the magnetosheath are observed close to the reconnection region, while the low energy ions, which take a longer time to reach the ionosphere, are detected farther away from it [5]. Ion dispersion provides also information on the reconnection process: a continuous reconnection produces a smooth energy dispersion curve while an intermittent reconnection produces steps in the dispersion [6].

Newell and Meng [7] reported the first observations of energy steps in ion dispersions. Steps were found in about 10% of the DMSP cusp crossings but were explained by acceleration processes in the reconnection region rather than by intermittent reconnection. On the other hand, Escoubet et al. [8] analyzed an event where the ion dispersion was marked by three distinct energy steps which they explained by the crossing of three successive FTEs, in agreement with the model developed by Cowley et al. [9]. Lockwood and Smith [6, 10] showed that the low-energy ion cut-off can give information about the history of the reconnection rate: a burst of reconnection is characterized by a constant energy cut-off (step) while a period with no reconnection is characterized by a jump in the cut-off. The application of that model to a DMSP pass 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 [11] using 21 DMSP crossings, showed that reconnection would rarely stop for more than one minute. Later, Lockwood et al. [12] demonstrated that precipitating and mirroring ions can be well modeled by a series of reconnection pulses lasting 0.5-2.5 min. separated with 1-3 min. of slow reconnection.

Proceedings Cluster and Double Star Symposium – 5th Anniversary of Cluster in Space, Noordwijk, The Netherlands, 19 - 23 September 2005 (ESA SP-598, January 2006)

Quasi-continuous reconnection was again put forward when quasi-simultaneous observations of the polar cusp became available. First, Onsager et al. [13] found a pair of DE-1 and DE-2 crossings of the cusp 20 min. apart, that displayed discontinuities in ion dispersions at about the same invariant latitude. Trattner et al. [14] showed very similar structures in the ion dispersion observed by Polar and Interball, separated by 1.5 hr. in time. Later on, Trattner et al. [15] 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.

This paper reports the time evolution of an ion step observed during consecutive crossings of the mid-altitude polar cusp by the four Cluster spacecraft on 7 Aug. 2004. The next section presents the solar wind conditions and ion and electron data from the Cluster spacecraft. We conclude the paper by discussing the observations in terms of new injection in the polar cusp.

2. OBSERVATIONS

2.1 Interplanetary conditions and Cluster orbit

The magnetic field and solar wind dynamic pressure on 7 Aug. 2004 are displayed in Figure 1. The ACE spacecraft was located at the L1 point.

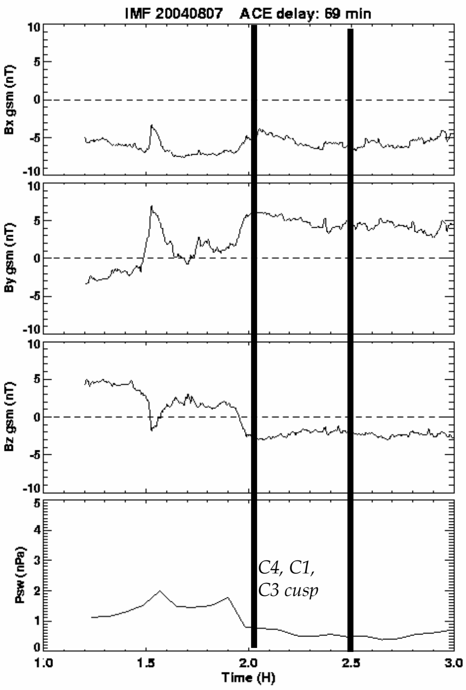

Figure 1: solar wind conditions on 7 Aug. 2004 from the ACE spacecraft. A shift of 69 min was applied to the data to take into account from the propagation to the front of the magnetosphere.

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. Then, just before the cusp crossings, Bz turned southward then stayed constant around -2 nT, By increased from 2 to 5 nT and Bx was about -5 nT. The solar wind pressure was fairly low at around 1.5 nPa and then dropped to 0.8 nPa before the cusp crossing.

The four Cluster spacecraft crossed the polar cusp at an altitude of 4.5 R_E between 02 and 03 UT (Figure 1). The spacecraft were following each other with C4 leading, then C1 following 4 min. later, C2, 9 min. later and finally C3 18 min. later. The spacecraft are exactly on the same meridian plane (bottom panel on Figure 1) and the separations in invariant latitude (ILAT) are 0.5, 1.2 and 2.5 deg between C4 and C1, C4 and C2 and C4 and C3 respectively. The width of the polar cusp being around 3 deg. ILAT, all four spacecraft are within the cusp at the same time.

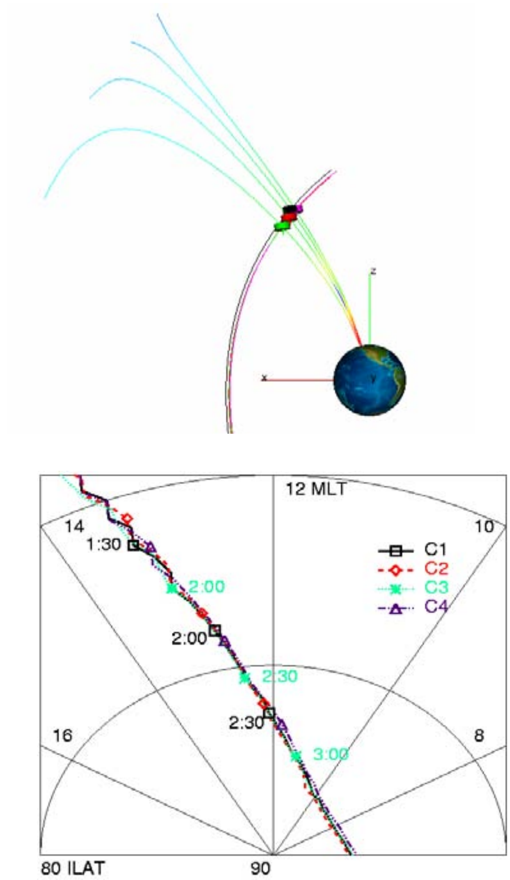

Figure 2: Cluster orbit in GSE XZ plane at 02:10 (top) and projection of orbit track in ILAT-MLT diagram (bottom). The colours of the spacecraft are the usual Cluster colours (C1, black, C2 red, C3, green and C4 magenta). The time delays and the separations of the spacecraft in latitude are dt41=4 min, dt42=9 min, dt43=18min and dlat41=0.5^o, dlat42=1.2^o, dlat43=2.5^o

2.2 Cluster observations

The ion and electron precipitations observed by the four Cluster spacecraft in the polar cusp are shown in Figure 3. 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 in Figure 3) and entered the cusp, C1 at 02:03:02 UT, C2 at 02:06:00 UT and C3 at 02:10:40 UT. The cusp is characterised by a high flux of ions in the range of 50 eV to 3 keV and an increase of electron flux below a few 100s eV. The average motion of the OCB between two spacecraft crossings can be estimated by using the crossing times of the OCB by each spacecraft and their position in invariant latitude . We found that the OCB was moving equatorward during the crossings and that its speed was initially -0.43^{o} ILAT/min between C4 and C1, and then -0.16^{o} ILAT/min between C1 and C2, and -0.16^{o} ILAT/min between C2 and C3.

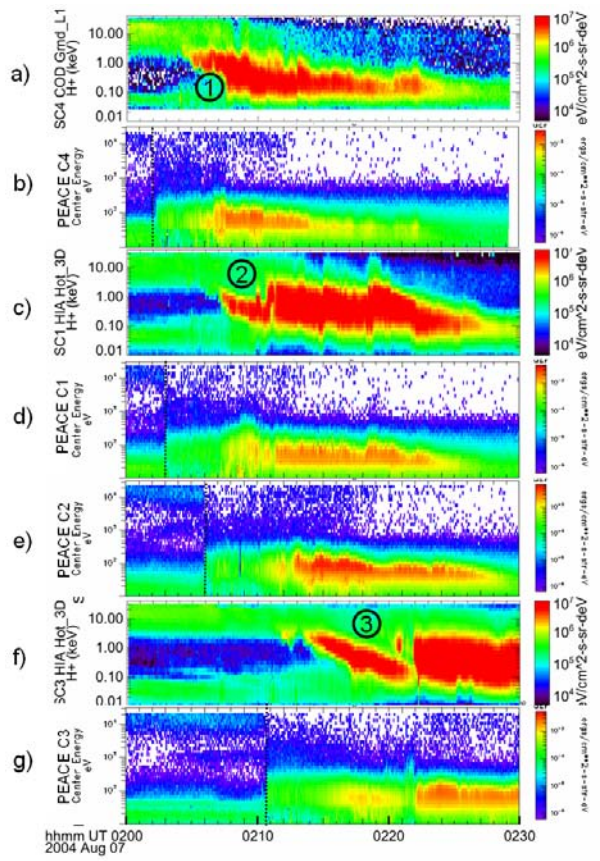

Figure 3: Omnidirectionnal ion and downgoing electron spectrograms on C4 (panels a, b), C1 (panels c, d), C2 (panel e), and C3 (panels f, g). Open-Closed Boundary is indicated by the dotted line on the electron spectrograms. The ion energy steps and dispersions are marked from 1 to 3.

At around 02:06 UT, the C4 spacecraft observed an ion step at about 1 keV (Figure 3a). This step is defined by the sudden drop of the low energy cut-off of the ions. About 3 min. later, C1 observed a step around 400 eV (Figure 3c) but now this step is in the high energy cut-off instead of being in the low energy cut-off. Finally, 10 min. later, C3 observed a complete ion dispersion (Figure 3f). 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) and enhanced flux around 1 keV. Poleward of the step the 1 keV electrons disappeared and the flux of electron below 100 eV increased significantly.

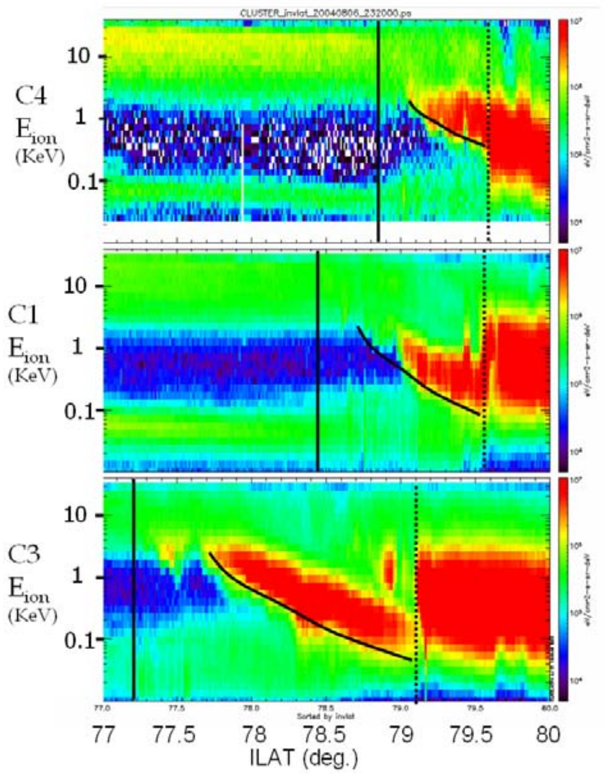

Figure 4: Omnidirectionnal ion spectrograms as a function of invariant latitude for C4 (top), C1 (middle) and C3 (bottom).OCB is marked by a solid vertical line and the boundary between the energy steps/dispersion and the main cusp is marked by a dotted line.

To easily compare the ion step observed by each spacecraft we have plotted the 3 spacecraft ion spectrograms as a function of invariant latitude (Figure 4). We can clearly see the motion of the OCB (solid vertical line) to lower latitudes between C4, C1 and C3. The boundary between the energy step/dispersion and the main cusp (dotted vertical line) is also moving equatorward but at a slower rate (-0.03^{o} ILAT/min) than the OCB. The energy step observed by C4 (top panel) shows a decreasing energy of the 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 (middle panel) sees a longer dispersion than C4; the low energy cut-off starts from 2 keV and reaches 100 eV. The size of the dispersion 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. A short discontinuity is observed in the centre of the ion energy dispersion; 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. Detailed views of the ion distribution functions (not shown) revail that during the burst the distribution is similar to the one observed at the beginning of the dispersion (around 77.7° ILAT) which suggests that the OCB has moved poleward and then equatorward again, producing a gap in the precipitation of the ions.

The convection flows measured by C1 and C3 are shown in Figure 5. In the energy step on C1 (around 02:09 UT) and in the ion dispersion on C3 (around 02:17 UT), the flow was mainly poleward (x component of the flow negative on panels b and e) with a small component westward (y component of the flow positive on panels c and f) and in the poleward part of the cusp, the flow was mainly eastward with two main peaks above 10 km/s.

3. DISCUSSION AND CONCLUSION

The consecutive cusp crossings of the four Cluster spacecraft allow us to observe the changes occurring in the polar cusp on 7 Aug. 2004. These crossings occurred just 8 min. after the southward turning of the IMF. The equatorward motion of the OCB observed by the spacecraft indicates a clear erosion of the magnetosphere. The rate was high between the first two spacecraft (-0.43° ILAT/min) as compared to the last two spacecraft (-0.16° ILAT/min). Our findings are consistent with previous studies that have measured an equatorward shift of the cusp in the range of -0.2 to -0.3° ILAT/min after the southward turning of the IMF [16, 17]. We find that the initial shift of the cusp is faster in the first minute than afterwards. This suggests that the reconnection rate was higher at the onset of reconnection and then slowed down with time.

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 one (C1) observed a wider step, around 0.8° ILAT, and the low energy cut-off decreasing from 2 keV down to 100 eV. Finally C3 observed a full dispersion extending over 1.5° ILAT and with a low energy cut-off from 2 keV down to 50 eV.

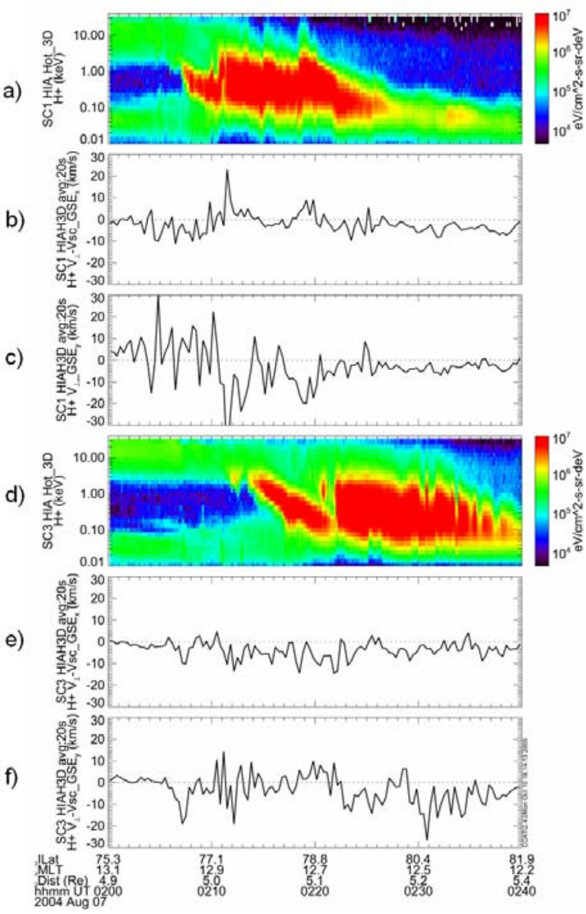

Figure 5: Ion spectrograms and flow speed from C1 and C3. The X_{GSE} components of the flow are shown on panels b and e (with positive directed sunward). The Y_{GSE} components of the flow are shown on panels c and f (with positive directed Eastward).

We will now show that the energy step and dispersions can be explained by the start-up of plasma injection at the dayside magnetopause after the southward turning of the IMF. A sketch of the time evolution of the injection is shown in Figure 6. For simplicity we show only three energies of ions but in reality all ions from a few 10s of eV up to a few KeV are present. Let us assume that the injection (source) starts at time t_1, which coincides with the arrival of the southward turning of the IMF at the dayside magnetopause.. At time t_2 C4 observes the first high-energy ions arriving from the source. Then at t_3 C1 observes a step or incomplete dispersion because low energy ions have not arrived yet, and finally at t_4, C3 observes the full dispersion.

The observation of high energy ions on the three spacecraft crossings, near the OCB, implies that the injection was continuous between the first and the last spacecraft crossing, or about 10 min. The low flux of high energy ions (2 keV) observed by C1 could indicate a fluctuation in the injection, however more inter-calibrations between the spacecraft are necessary to confirm it.

In conclusion, Cluster multi-spacecraft crossings of the mid-altitude cusp on 7 Aug. 2004 show the occurrence of a step in ion energy dispersion a few minutes after the southward turning of the IMF. While in the past ion energy steps were associated with the acceleration of ions by the reconnection process [7] or alternatively by pulsed reconnection [6, 8] our analysis of that event suggests that the step was created by the start of a new injection on the dayside magnetopause. This injection was caused by a burst of reconnection triggered by the southward turning of the IMF. Then reconnection kept going, resulting in the erosion of the dayside magnetosphere while the ion dispersion grew in size to finally reach its full extent after 10 min.

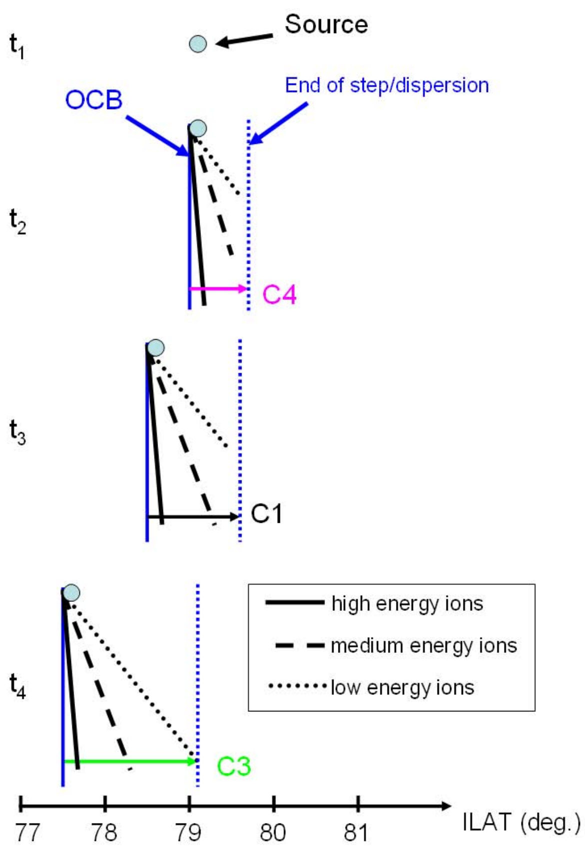

Figure 6: Sketch of the start of the injection and the subsequent observation by C4, C1 and C3.

4. REFERENCES

1. Goertz, C. K., E. Nielsen, A. Korth, K. H. Glassmeier, C. Haldoupis, P. Hoeg, and D. Hayward, Observations of a possible ground signature of flux transfer events, *J. Geophys. Res*., *90*, 4069-4078, 1985.

2. Basinska, E. M., W. J. Burke, and M. A. Heinemann, A user's guide to locating flux transfer events in low-altitude satellite measurements - An S3-2 case study, *J. Geophys. Res.*, *94*, 6681-6691, 1989.

3. Southwood, D. J., The ionospheric signature of flux transfer events, *J. Geophys. Res*., *92*, 3207-3213, 1987.

4. Lockwood, M., and M. F. Smith, Low-altitude signatures of the cusp and flux transfer events, *Geophys. Res. Lett., 16*, 879-882, 1989.

5. Reiff, P. H., J. L. Burch, and T. W. Hill, Solar wind plasma injection at the dayside magnetospheric cusp, *J. Geophys. Res.*, *82*, 479-491, 1977.

6. Lockwood, M., and M. F. Smith, The variation of reconnection rate at the dayside magnetopause and cusp ion precipitation, *J. Geophys. Res*., *97*, 14,841– 14,847, 1992.

7. Newell, P. T., and C.-I. Meng, Ion acceleration at the equatorward edge of the cusp: Low-altitude observations of patchy merging, *Geophys. Res. Lett*., *18*, 1829–1832, 1991.

8. Escoubet, C. P., M. F. Smith, S. F. Fung, P. C. Anderson, R. A. Hoffman, E. M. Basinska, and J.-M. Bosqued, Staircase ion signature in the polar cusp – A case study, *Geophys. Res. Lett.*, *19*, 1735-1738, 1992.

9. Cowley, S. W. H., J. P. Morelli, and M. Lockwood, Dependence of convective flows and particle precipitation in the high-latitude dayside ionosphere on the X and Y components of the interplanetary magnetic field, *J. Geophys. Res.*, *96*, 5557-5564, 1991.

10. Lockwood, M., and M. Smith, Low and middle altitude cusp particle signatures for general magnetopause reconnection rate variations: 1. Theory, *J. Geophys. Res*., *99*, 8531–8554, 1994.

11. Newell, P. T. and C.-I. Meng, Cusp low-energy ion cutoffs: A survey and implications for merging, *J. Geophys. Res.*, *100*, 21943-21952, 1995.

12. Lockwood, M., C. J. Davis, T. G. Onsager, and J. A. Scudder, Modeling signatures of pulsed magnetopause reconnection in cusp ion dispersion signatures seen at middle altitudes, *Geophys. Res. Lett*., *25*, 591– 594, 1998.

13. Onsager, T. G., S.-W. Chang, J. D. Perez, J. B. Austin, L. X. Janoo, Low-altitude observations and modeling of quasi-steady magnetopause reconnection, *J. Geophys. Res*., *100*, 11831-11844, 1995.

14. Trattner, K. J., S. A. Fuselier, W. K. Peterson, J.-A. Sauvaud, H. Stenuit, and N. Dubouloz, On spatial and temporal structures in the cusp, *J. Geophys. Res*., *104*, 28,411, 1999.

15. Trattner, K. J., S. A. Fuselier, W. K. Peterson, and C. W. Carlson Spatial features observed in the cusp under steady solar wind conditions, *J. Geophys. Res*., *107*(A10), 1288, doi:10.1029/2001JA000262, 2002.

16. Sandholt, P. E., C. J. Farrugia, L. F. Burlaga, J. A. Holtet, J. Moen, B. Lybekk, B. Jacobsen, D. Opsvik, A. Egeland, R. Lepping, A. J. Lazarus, T. Hansen, A. Breckke, and E. Friis-Christensen, Cusp/cleft auroral activity in relation to solar wind dynamic pressure, interplanetary magnetic field B(sub z) and B(sub y), *J. Geophys. Res.*, *99*, 17,323-17,342, 1994.

17. Nishitani, N., T. Ogawa, N. Sato, H. Yamagishi, M. Pinnock, J.-P. Villain, G. Sofko, et O. Troshichev, A study of the dusk convection cell's response to an IMF southward turning, *J. Geophys. Res.*, *107*(A3), 1036, doi:10.1029/2001JA900095, 2002.