MECHANISM FOR THE FORMATION OF THE HIGH-ALTITUDE STAGNANT CUSP: CLUSTER AND SUPERDARN OBSERVATIONS

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ABSTRACT

On 16 March 2002, Cluster moved from nightside to dayside, across the high-altitude northern cusp during an extended period of relatively steady positive IMF B_Y and B_Z. Combined Cluster and SuperDARN data imply the existence of two reconnection sites: in the high-latitude northern hemisphere dusk and southern hemisphere dawn sectors. Within the cusp, Cluster encounters 3 distinct plasma regions. First, injections of magnetosheath-like plasma associated with dawnward and sunward convection suggest Cluster crosses newly-reconnected field lines related to the dusk reconnection site. Second, Cluster observes a Stagnant Exterior Cusp (SEC), characterized by nearly isotropic and stagnant plasma. Finally, Cluster crosses a region with significant antifield-aligned flows. We suggest the observed SEC may be located on newly re-closed field lines, reconnected first poleward of the northern hemisphere cusp and later reconnected again poleward of the southern hemisphere cusp. We discuss how the Cluster observations correspond to expectations of 'double reconnection' model.

1. INTRODUCTION

The importance of the reconnection process in the formation of the cusps has been extensively studied, and it is now understood that the cusp can be populated by plasma entry from either dayside or lobe reconnection, depending on the Interplanetary Magnetic Field (IMF) orientation [1, 2]. Moreover, it was suggested that lobe and sub-solar reconnection could occur simultaneously under northward IMF [3]. Song and Russell [4] and Lockwood and Moen [5] discussed reconnection geometries during northward IMF and suggested that open magnetic field lines reconnected at high-latitudes in one hemisphere, could be re-reconnected in the other hemisphere, thus creating newly closed field lines. The order of occurrence of reconnection at the two sites depends on the dipole tilt and on IMF B_X.

The interface between the high-altitude cusp and the magnetosheath has been the topic of debate since Paschmann et al. [6] and Haerendel et al. [7] proposed the existence of the 'entry layer' and 'stagnation region'. The existence of this latter region, the Stagnant Exterior Cusp (SEC), within the high-altitude cusp was confirmed recently by Cluster [e.g., 8]. However, the processes forming the SEC are still uncertain.

In this paper we discuss Cluster observations of the high-altitude cusp under steady northward IMF during the period 0530–0900 UT on 16 March 2002. The observations were previously presented by Lavraud et al. [8]. We use the SuperDARN radar data in order to examine ionospheric plasma convection and constrain the location of particle injections into the magnetosphere. We suggest the characteristics of the SEC can be explained as this region being located on re-closed magnetic field lines. These field lines appear to have been first opened by reconnection on the northern lobe magnetopause and subsequently re-closed by a second reconnection with older open field lines on the southern lobe magnetopause.

2. INSTRUMENTATION, CLUSTER ORBIT AND SOLAR WIND CONDITIONS

We use Cluster data from the Plasma Electron and Current Experiment (PEACE) [9], the Hot Ion Analyzer (HIA) and Composition and Distribution Function (CODIF) sensors of the Cluster Ion Spectrometer (CIS) [10] and the Flux Gate Magnetometer (FGM) [11]. Ionospheric plasma convection is derived from measurements of 2 coherent HF radars of the SuperDARN network [12].

At ~0605 UT on March 16, 2002, the centroid of the 4 Cluster spacecraft was located at (1.96, -0.18, 7.55) R_E GSM and 1148 MLT. Over the next 2 hours the spacecraft moved ~3 R_E in the +X GSM direction, but remained near noon MLT and within the cusp. Cluster inter-spacecraft separations were only 50–150 km, so the plasma properties observed at each spacecraft are

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

similar. We thus present Cluster observations from SC1 only.

During the period of interest the IMF, observed by the WIND spacecraft located at (34, -130, -55) R_E GSM, had a strong northward GSM component, B_Z = 3–6 nT, and pointed duskward, B_Y ~ 2–6 nT, and steadily antisunward, B_X = -4 nT (see [8], Figure 2). The IMF clock-angle was in the range (30° ± 15°). The solar wind dynamic pressure was 3.5–4 nPa, decreasing at the end of the interval. The IMF configuration during the event suggests that anti-parallel merging may take place on the northern lobe magnetopause in the dusk sector [13].

3. CLUSTER OBSERVATIONS

An overview of Cluster particle and magnetic field data is shown in Figure 1. Panel (a) presents differential energy flux of electrons of energy 20–820 eV. The 9 subpanels show the pitch-angle distribution (0°–180°) for the energy channel centered on the value given on the left of the panel. Panel (b) shows the H^+ energy-time spectrogram measured by CODIF. Panel (c) presents energy-time spectrogram of 5 keV < E < 28 keV ions measured by HIA. Panels (d) and (e) present the pitch-angle spectrograms of E = 20–100 eV and E = 0.1–3 keV H^+ ions respectively. Panel (f) shows electron anisotropy $T_{||e}/T_{\perp e}$. The H^+ (red) and electron (black) parallel velocities, $V_{||}$, are shown in panel (g), while the corresponding two GSM components of the perpendicular velocities, $V_{\perp X}$ and $V_{\perp Y}$, are shown in panels (h) and (i) respectively. The final three panels present the GSM components B_Z, B_Y, B_X of the magnetic field.

At the beginning of the interval shown, Cluster was in the north lobe, but crossed the poleward boundary of the high-altitude cusp at ~0605 UT [8]. This region (Region 1 in Figure 1) is characterized by the appearance of strong down-going magnetosheath-like ion injections (panels d, e, g) and high fluxes of bi-directional, short-duration electron beams (a) with large temperature anisotropy (f) and net field-aligned flow (g). The parallel velocities of H^+ ions and electrons were high, ~270–310 km s^{-1} (g). Plasma convection past the spacecraft was mainly dawnward (-60 ≤ $V_{\perp Y}$ ≤ 0 km s^{-1}, panel (i)) and sunward (0 ≤ $V_{\perp X}$ ≤ 45 km s^{-1}, panel (h)). Particle signatures in this region are in agreement with plasma injections from the anti-parallel dusk-lobe reconnection site. The magnetic field configuration (j–l) shows that Cluster crossed field lines which were directed earthward and anti-sunward (B_Z < 0, B_X < 0).

At ~0710 UT Cluster entered the SEC, marked as Region 2 and defined for this event by Lavraud et al. [8] as a region of highly-isotropic, stagnant H^+ ions and magnetic field strength depression. However, electrons

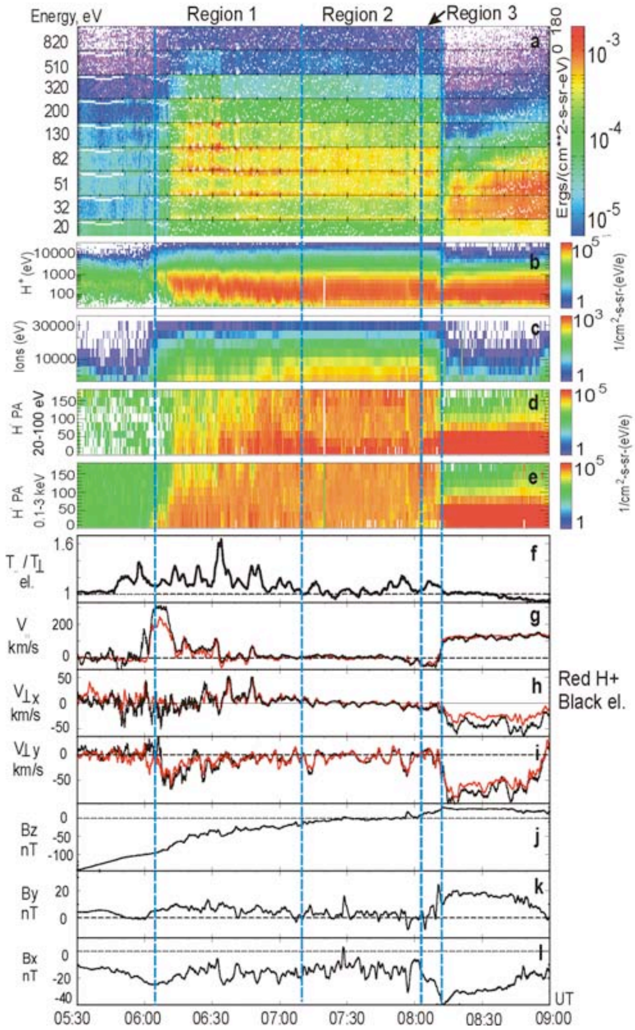

Fig. 1. Cluster data for 16 March 2002. See text for details.

inside the SEC are isotropic only for ~30 minutes from ~0718 UT, when $T_{||e}/T_{\perp e}$ ~ 1. Before and after this period in the SEC region, electrons with energies E = 20–200 eV have higher fluxes in the parallel and anti-parallel directions than in perpendicular direction (a) such that $T_{||e}/T_{\perp e}$ > 1. In addition, the degree of proton isotropy is a function of particle energy: while the E = 0.1–3 keV H^+ ions were near isotropic (e), the 20 < E < 100 eV proton population remains anisotropic (d), with higher parallel and antiparallel fluxes. Also from ~0700 UT, a strong flux enhancement of 5 keV < E < 10 keV ions was detected (c), and continued throughout the SEC crossing. The parallel velocities of both ions and electrons inside the SEC are very small (g). The sunward component of the perpendicular plasma velocity was also small (h), while a slow dawnward convection, (-20 ≤ $V_{\perp Y}$ ≤ 0 km s^{-1}, panel (i)) was evident (cf. Cluster spacecraft motion sunward at ~3 km s^{-1}). The magnetic field in this region was very weak and directed anti-sunward (-10 < B_X < -20 nT, B_Y ~ B_Z ~ 0).

Between ~0801–0813 UT (Region 3 in Figure 1), the parallel velocity of both protons and electrons turned negative, at ~-60 km s^{-1}. Examination of H^+ pitch-angle distributions shows that low-energy (20 < E < 100 eV) ions move mostly parallel to the field while ions with higher energy (E = 0.1–3 keV) move in the anti-parallel direction. The fluxes of 5 keV < E < 10 keV ions show a monotonic decrease during this period. Electrons with energies E = 25–150 eV show bi-directional streaming along the field with slightly higher anti-parallel fluxes than parallel. Plasma convection showed a small increase in the anti-sunward direction. From 0801 UT the B_Z and B_Y components become increasingly positive, while the B_X component remained dominant and monotonically increased to ~ -40 nT by the end of this interval. At ~0813 UT Cluster crossed into the magnetosheath (see [8] for details).

4. IONOSPHERIC CONVECTION AND RECONNECTION GEOMETRY

There is no radar coverage in the dusk sector, but the noon and dawn sectors were in the field of view of the CUTLASS Hankasalmi (H) and Thikkvibaer (T) radars (at 59.78° and 64.59° MLAT respectively). At 07:00 UT these radars are located at 09:08 and 06:46 MLT respectively. Figure 2 shows range-time plots of the line-of-sight (l-o-s) velocity from three different beams of these radars. Positive (negative) velocities represent plasma motion towards (away from) the radar. During the time of interest, beam 12 from the H radar (Figure 2a) points mainly duskward and detects plasma convection at 12–13 MLT and 76–82° MLAT, close to the Cluster footprint moving between 76–79° MLAT at ~11:50 MLT. Beam 2 from the T radar (Figure 2b) also points mainly duskward, monitoring convection a t 10–12 MLT and 79–82° MLAT. Finally, beam 2 from the H radar (Figure 2c) points in the duskward/poleward direction and detects convection in the dawn sector, 5:30–7:30 MLT and 76–80° MLAT.

When Cluster was in Region 1, strong dawnward plasma convection in the ionosphere at speeds of 400–700 m s^{-1} is observed near the Cluster footprint (Figure 2a) together with dawnward convection at speeds of 200–600 m s^{-1} in the pre-noon sector (Figure 2b). Dawnward ionospheric convection is in agreement with Cluster observations of the plasma injections from the dusk-lobe reconnection site. When Cluster was in the SEC, the ionospheric data near the Cluster footprint (Figure 2a) were very sparse, most likely due to the absence of plasma irregularities. However, poleward and dawnward of Cluster, in the pre-noon sector, dawnward convection continues at speeds of 100–500 m s^{-1} (Figure 2b). The lack of change in the convection pattern in this sector strongly suggests that the duskside anti-parallel merging site continued to operate while Cluster was in the SEC.

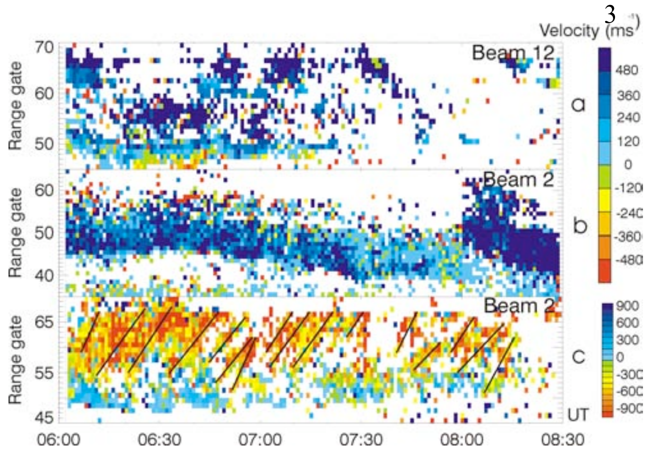

Fig. 2. Ionospheric velocity range-time plots for Hankasalmi (a, c) and Thikkvibaer (b) radars. Range gates represent distance along the beam direction from the radar to the source of the echoes in units of ~45 km length. Note Figures 2a and 2b have a different color scale from Figure 2c. See text for details.

Throughout the entire time of interest, a region of enhanced anti-sunward and duskward convection was detected by the H radar's beams 1–5 in the dawn sector, 6–9 MLT and 78–83° MLAT. Figure 2c shows well defined repetitive Pulsed Ionospheric Flows (PIFs, black lines), which usually are interpreted as ionospheric signatures of FTEs [e.g., 14] from an active reconnection site. The location of the detected PIFs maps along magnetic field lines to the dawn-lobe magnetopause. This indicates that a second reconnection site operates in the dawn sector, and that this also persisted for the 2 hours that Cluster was in the Region 1 and SEC.

5. DISCUSSION AND INTERPRETATION

The relatively smooth transitions in the plasma and magnetic field properties as Cluster enters the SEC from the Region 1 at ~0710 UT, suggests that the SEC region is not an isolated region but evolves from the high-altitude cusp proper. However, the absence of energy-latitude dispersions, the low levels of convection and bulk parallel flow and the near isotropy of the plasma in the SEC are not consistent with the SEC being located on 'open' reconnected field lines. We believe the possible explanation for the formation of this exterior cusp is based on observations that two reconnection sites were active on the magnetopause. We thus consider the possibility that the SEC is formed on field lines that are first opened at one of these reconnection sites operating in one hemisphere, but then re-closed at the other reconnection site in the other hemisphere [4, 15]. Since IMF B_X was negative, we expect reconnection to have occurred first in the northern hemisphere and later in the southern hemisphere. If such a reconnection configuration exists, then Cluster, moving from nightside to dayside, may cross several different regions as illustrated schematically in Figure 3a: firstly the magnetospheric parts of field lines reconnected only in the northern hemisphere; then those re-closed by undergoing a second reconnection in the southern hemisphere; and finally, the magnetosheath part of the field lines reconnected only in the northern hemisphere.

Between 0605–0710 UT, the dawnward and sunward plasma convection at Cluster, as well as in the ionosphere near 12 MLT indicate that Cluster was located on field lines reconnected on the northern lobe-dusk magnetopause. The anti-sunward magnetic field orientation ($B_Z < 0$, $B_X < 0$) corresponds to inner magnetospheric part of the cusp throat. The parallel velocity dispersion (Figure 1g) can be explained by Cluster moving onto field lines with longer time histories since reconnection. Thus the data indicate that Cluster was on open field lines in the inner part of the cusp throat and observing plasma injection from reconnection on the northern hemisphere, dusk-side lobe magnetopause. We thus associate Region 1 in Figure 3a with the cusp proper (CP).

Inside the SEC region, between 0710 and 0801 UT, Cluster moved sunward by 1.5 R_E and higher in altitude by 0.27 R_E. Initially, the magnetic field had similar orientation to the CP, consistent with remaining within the magnetospheric part of the cusp throat. However, after 0730 UT, $B_Y \sim B_Z \sim 0$, consistent with the spacecraft being located near the 'turn-over' part of dayside magnetic field lines. Inside the SEC, convection was very slow, consistent with magnetic field lines which have become disconnected from the solar wind driver. Onsager et al. [15] suggest that particles populating re-closed flux tubes may have undergone multiple accelerations at the two reconnection sites and thus would be hotter than those accelerated once on an open field line. The observation of the strong enhancement of ion flux at energies 5–10 keV is thus consistent with the 'double reconnection' hypothesis. Parallel and anti-parallel fluxes on re-closed field lines should initially exceed perpendicular fluxes, as observed in low-energy ions. However, due to pitch angle scattering, distributions should become more isotropic ($T_{\parallel e}/T_{\perp e} \sim 1$) with time, especially for the higher energy ions and electrons with shorter bounce times, as is also observed during this period. These characteristics are all thus consistent with the SEC being located on re-closed field lines (Region 2 in Figure 3a).

Between 0801 and 0813 UT, the observed magnetic field rotates monotonically towards the magnetosheath orientation and increases in strength, while the plasma convection increases and becomes anti-sunward, also more typical of the magnetosheath. The high-energy (5 keV < E < 10 keV) ions disappear. In this region, there is a net antifield-aligned flow of both electrons and ions, so particle fluxes away from the northern ionosphere

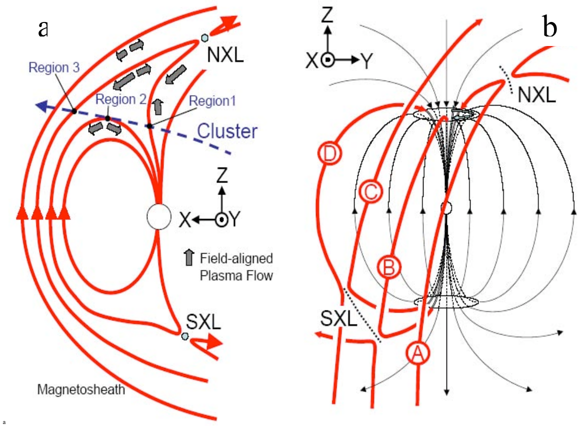

Fig. 3. Magnetic field configuration with two (North and South) X-lines (NXL and SXL) and Cluster trajectory.

exceed those towards it. However, low energy H^+ is concentrated at pitch angles < 60°, and thus observed to be moving towards the likely northern hemisphere high-latitude reconnection site, while the higher energy protons peak at > 120° and may thus represent the reconnection outflow. Similar behaviour can be discerned in the electron populations. These data are consistent with Cluster crossing out onto the magnetosheath portion of field lines which have been reconnected only once (Region 3 in Figure 3a).

The observations of enhanced anti-sunward and duskward flow in the dawnside sector by SuperDARN challenge our interpretation. Such enhanced flow is characteristic of reconnection of the magnetosheath field with closed 'dayside' field lines driving fast flows on newly opened field lines. However, note that for this IMF orientation, a flux tube reconnected poleward of the northern cusp and dragged sunward and dawnward (e.g. the field line marked 'A' in Figure 3b) cannot, in steady state, be convected over a neutral line operating on the dawn flank without being re-closed (field line 'B'). Alternatively, draping of the magnetosheath field may provide sufficient shear to allow component reconnection [e.g., 16] on the dawnside between magnetosheath flux and closed dayside flux tubes, to result in open flux tubes (marked 'C' and 'D'), one of which is magnetically connected to the northern dawnside polar regions. We therefore conclude that the south X-line extends across the interface between closed dayside and open lobe type flux tubes in order to create field lines of both types 'B' and 'D'.

6. CONCLUSION

During this event, Cluster and SuperDARN data suggest the existence of two stable reconnection sites: one in the dusk sector of the northern hemisphere and another in the dawn sector of the southern hemisphere. Cluster, moving along the noon meridian, first detects plasma injections from the dusk sector, consistent with high-latitude northern hemisphere anti-parallel merging. It subsequently moved into a stagnant exterior cusp region, where the particle populations could be explained as being located on field lines that have been re-closed by the reconnection in the dawn sector in south hemisphere, as suggested by SuperDARN data. Finally, before entering the magnetosheath proper, the spacecraft cross a region with characteristics consistent with the exterior portion of those field lines reconnected only at the high-latitude northern hemisphere anti-parallel merging site. Our primary conclusion, therefore, is that in this event the stagnant exterior cusp is formed on field lines that have undergone 'double reconnection', being first opened in the northern hemisphere and subsequently re-closed by southern hemisphere reconnection. The re-closing of these field lines decouples the region from the influence of the solar wind flow, and thus accounts for the lack of significant convection, the lack of particle injections and the closely isotropic nature of the plasma populations.

ACKNOWLEDGMENTS

This work was sponsored by the UK Particle Physics and Astronomy Research Council. We thank CDAWeb, A. Balogh and H. Reme for WIND, FGM and CIS data respectively. We acknowledge discussions with participants of the UK Cluster/Ground-based workshops.

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