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Simultaneous Cluster and IMAGE observations of cusp reconnection and auroral proton spot for northward IMF

T. Phan,[1] H. U. Frey,[1] S. Frey,[1] L. Peticolas,[1] S. Fuselier,[2] C. Carlson,[1] H. Rème,[3]
J.-M. Bosqued,[3] A. Balogh,[4] M. Dunlop,[5] L. Kistler,[6] C. Mouikis,[6] I. Dandouras,[3]
J.-A. Sauvaud,[3] S. Mende,[1] J. McFadden,[1] G. Parks,[1] E. Moebius,[6] B. Klecker,[7]
G. Paschmann,[7] M. Fujimoto,[8] S. Petrinec,[2] M. F. Marcucci,[9] A. Korth,[10] and R. Lundin[11]

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[1] On March 18, 2002, under northward interplanetary magnetic field (IMF) and high (~15 nPa) solar wind dynamic pressure conditions, Cluster observed reconnection signatures and the passage of an X-line at the large (~175°) magnetic-shear high-latitude magnetopause (MP). The observations are consistent with the occurrence of a reconnection site tailward of the cusp and in the vicinity of the spacecraft. At the same time IMAGE observed a bright spot poleward of the dayside auroral oval resulting from precipitating protons into the atmosphere. The intensity of the proton spot is consistent with the energy flux contained in the plasma jets observed by Cluster. Using the Tsyganenko-01 magnetic field model with enhanced solar wind pressure, the Cluster MP location is mapped to the vicinity of the IMAGE proton spot. Mapping the auroral spot out to the MP implies an X-line of at least 3.6 R_E in y_{GSM}. In addition to confirming the reconnection source of the dayside auroral proton spot, the Cluster observations also reveal sub-Alfvénic flows and a plasma depletion layer in the magnetosheath next to the MP, in a region where gas dynamic models predict super-Alfvénic flows. *INDEX TERMS:* 7835 Space Plasma Physics: Magnetic reconnection; 2407 Ionosphere: Auroral ionosphere (2704). **Citation:** Phan, T., et al., Simultaneous Cluster and IMAGE observations of cusp reconnection and auroral proton spot for northward IMF, *Geophys. Res. Lett.*, *30*(10), 1509, doi:10.1029/2003GL016885, 2003.

1. Introduction

[2] In-situ observations have established the occurrence of reconnection at the low-latitude magnetopause (MP) [e.g., *Sonnerup et al.*, 1981] as well as the high-latitude MP involving lobe fields [e.g., *Gosling et al.*, 1991]. However, the large-scale nature of MP reconnection is largely unknown from in-situ observations due to the lack of simultaneous observations at many MP locations.

[3] It has been suggested that dayside auroral emissions are driven by MP reconnection and provide a means to remotely monitor the locations and extents of the MP reconnection sites [e.g., *Milan et al.*, 2000; *Frey et al.*, 2002]. *Fuselier et al.* [2002] reported that the dayside proton aurora emissions show distinct differences for northward and southward IMF. For southward IMF, the auroral oval near local noon is bright over a wide range of local times, whereas for northward IMF, a localized electron [*Milan et al.*, 2000] and ion [*Frey et al.*, 2002] spot of emission occurs poleward of the auroral oval. By mapping the proton emissions out to the MP, *Fuselier et al.* [2002] concluded that component merging across the entire dayside MP best describes the southward IMF situation, whereas under northward IMF conditions reconnection occurs tailward of the cusp and only in a localized region where the fields across the MP are nearly anti-parallel.

[4] The remote-sensing methods and interpretations need to be verified by in-situ measurements at the MP. One needs to confirm that reconnection does indeed occur at the time and at the location conjugate to the auroral emissions that are observed, and that the energy fluxes in the reconnection jets are consistent with the observed emissions. Here we report a Cluster/IMAGE conjunction under northward IMF conditions. Cluster encountered an X-line at the MP tailward of the cusp while IMAGE observed a proton aurora spot poleward of the oval, thus confirming the reconnection source of the spot.

2. Instrumentations and Orbits

[5] This study uses spin-resolution (4s) data from the Cluster ion composition (CIS) and magnetic field (FGM) experiments, as well as proton auroral images from the IMAGE/Spectrographic Imager (SI12) [*Rème et al.*, 2001; *Balogh et al.*, 2001; *Mende et al.*, 2000]. SI12 image exposures are 10 s and repeated every 2 min.

[6] On March 18, 2002, while Cluster was crossing the MP at 12.2 MLT, 77.8° magnetic latitude, and 7.5 R_E radical distance, IMAGE was near apogee over the north pole. The Cluster inter-spacecraft separation at the MP was ~100 km. At this small separation, the MP structures appear nearly identical on all spacecraft in 4s resolution data. Thus data from only one spacecraft is shown.

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[1] Space Science Laboratory, Berkeley, California, USA.
[2] Lockheed Martin Adv. Tech. Cent., Palo Alto, California, USA.
[3] Centre d'Etude Spatiale des Rayonnements, Toulouse, France.
[4] Imperial College, London, UK.
[5] Rutherford Laboratory, Oxford, UK.
[6] University of New Hampshire, Durham, New Hampshire, USA.
[7] Max-Planck-Institut für extraterrestrische Physik, Garching, Germany.
[8] Tokyo Institute of Technology, Meguro, Japan.
[9] Instituto di Fisica dello Spazio Interplanetario, Rome, Italy.
[10] Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Germany.
[11] Swedish Institute of Space Physics, Kiruna, Sweden.

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3. Observations

3.1. Solar Wind Conditions

[7] On March 18, 2002, ACE detected the arrival of an interplanetary shock at ~12:35 UT, and the solar wind density, speed, and pressure increased from their pre-shock values to ~40 cm^{-3}, ~470 km/s, and ~15 nPa and remained high until after 18:00 UT. Between 12:35 and 18:00 UT, IMF B$_z$ was large and positive while B$_y$ fluctuated between positive and negative values. The focus of the present paper is on a subset of this interval when Cluster encountered the high-latitude MP. Figures 1a–1c display the solar wind parameters (shifted by 49.2 min to match the Cluster measured magnetic field in the magnetosheath) for the 14:50–15:25 UT interval around the time of Cluster MP crossing. During this interval, the IMF B$_z$ was ~10 nT and the IMF B$_y$ was positive with variable magnitude.

3.2. IMAGE/SI12 Observations of the Proton Spot

[8] The high solar wind pressure and northward IMF conditions are expected to produce a dayside proton spot poleward of the auroral oval [*Frey et al.*, 2002]. Indeed, SI12 reveals the continuous presence of a dayside proton spot throughout the high solar wind pressure, northward IMF (5.5 hour) interval. Figure 2a shows an example at 14:58:56 UT where a bright proton spot centered at ~14 MLT and at ~81° latitude is evident. Figure 1d shows the peak and average intensities of the proton spot during the 35-min interval. The spot varies in intensity but is always clearly visible (more than 20 counts in peak intensity). The center of the spot moves back and forth in MLT but remains in the postnoon sector (Figure 1e). The postnoon location of the spot for positive IMF B$_y$ (Figure 1c) is consistent with the findings of *Coleman et al.* [2001] and *Frey et al.* [2002]. The variation of the spot MLT location is best correlated with changes in IMF B$_y$ if one assumes an additional delay of ~4 min for the auroral emission to respond to changes of the magnetosheath field next to the MP, roughly consistent with the ion travel time from the MP to the ionosphere.

3.3. Cluster Observations of Reconnection

[9] Figures 1g–1p show Cluster observations of reconnection jets and the crossing of an X-line at the MP at 14:54:52–15:03:52 UT (between the dashed lines). The MP crossing occurred tailward of the cusp and is recognized by the 175° rotation of the magnetic field from the lobe to the magnetosheath orientation (Figure 1o).

[10] Figure 1l shows the presence of plasma jets in the MP. Figure 1m shows that between 14:56:10 and 15:03:52 UT (interval 2 in Figure 1m), the flow enhancements (relative to magnetosheath flow) were sunward ($\Delta V_x > 0$), while $\Delta V_x <$ 0 between 14:54:52 and 14:56:10 UT (interval 1). Qualitatively, the flow behavior indicates that the spacecraft entered the MP from the lobe tailward of the X-line (at 14:54:52 UT) and then the X-line moved tailward past the spacecraft (at 14:56:10 UT) while the spacecraft was in the MP. The effective spacecraft trajectory through the reconnecting MP is shown schematically in Figure 3. The X-line crossing interpretation is further supported by the energetic O$^+$ behavior (Figures 1h–1i). Energetic (8–10 keV core energy) O$^+$ were seen throughout the sunward enhanced flow interval (14:56:10–15:03:52 UT). These ions are anti-field-aligned

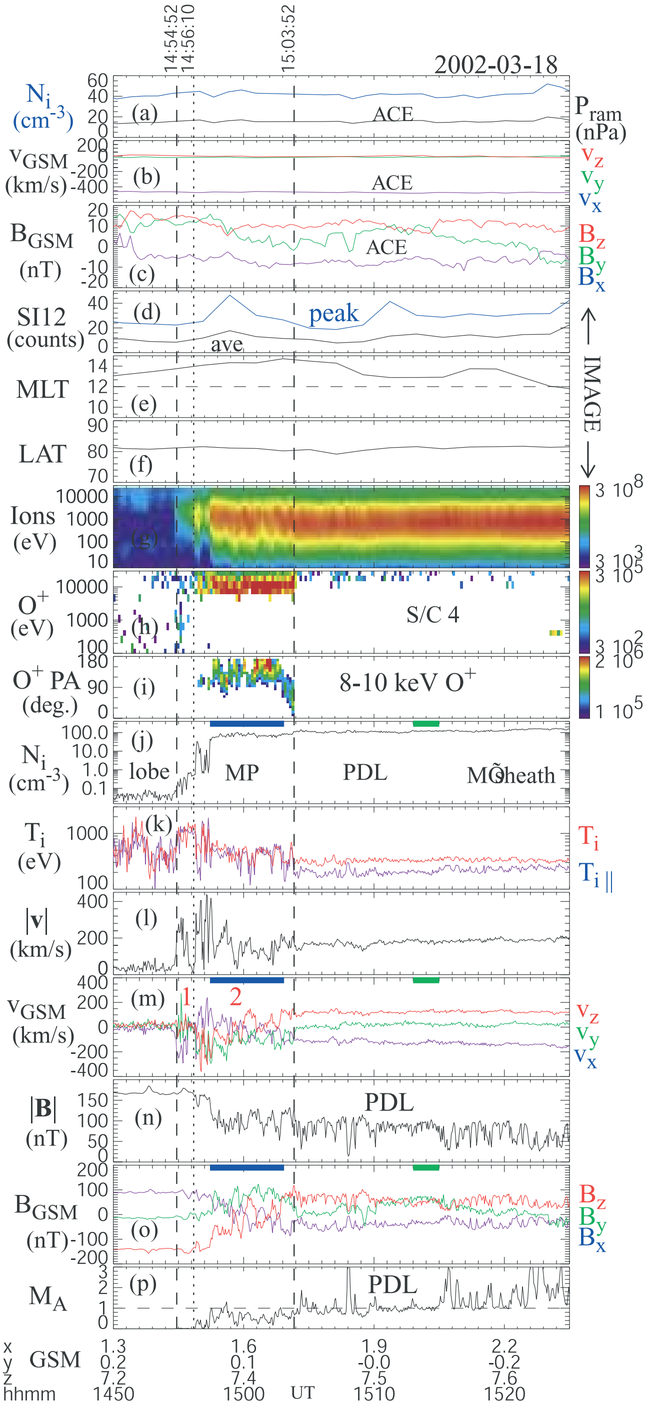

Figure 1. Solar wind (a) density and ram pressure, (b) velocity, (c) magnetic field, (d) IMAGE SI12 peak and average (500 × 500 km^2 around peak) counts, (e)–(f) MLT and latitude of peak SI12 intensity. (g)–(p) are Cluster data: (g) ion energy-time spectrogram (in eVs^{-1} cm^{-2} ster^{-1} eV^{-1}), (h) O$^+$, (i) energetic O$^+$ pitch angle, (j)–(m) ion density, temperatures, speed and velocity, (n)–(o) magnetic field magnitude and components, (p) Alfven Mach number based on tangential flow. Except for O$^+$, all Cluster data are from spacecraft 1. The interval between the dashed lines denotes the MP. Dotted line at 14:56:10 UT marks the flow reversal detected by Cluster. '1' and '2' in Panel (m) denote the regions tailward and earthward of the X-line, respectively.

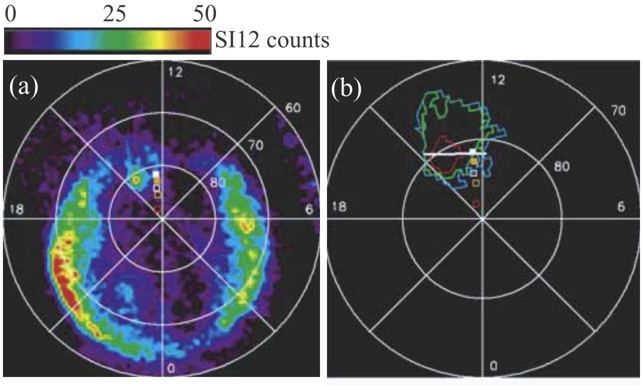

Figure 2. IMAGE/SI12 proton aurora image (in magnetic local time-latitude) on 2002-03-18 at 14:58:56 UT during the time Cluster was crossing the reconnecting MP tailward of the cusp. A bright proton spot poleward of the oval appears at ~14 MLT and ~81° latitude.

(Figure 1i) throughout the MP where the field rotates from the magnetosheath to the magnetosphere orientations, indicating that they originate from lower altitudes, not from the low-latitude MP. Consistent with the scenario of Figure 3 in which the region tailward of the X-line is detached from the low-altitude O^+ source, the >8 keV O^+ population is absent in interval 1 (14:54:52–14:56:10 UT).

[11] To confirm that the jets at the MP are due to reconnection, the Walén test [*Sonnerup et al.*, 1987] was performed. The MP and magnetosheath reference intervals for the Walén test are indicated by the blue and green bars, respectively, in Figures 1m and 1o. The MP interval encompasses nearly the entire current sheet, but excludes the tailward enhanced flows, which correspond to observations on the other side of the X-line. Figure 4a shows that a good deHoffmann Teller frame was found, and the flow velocity in this frame is 90% of the Alfvén velocity (Figure 4b), in good agreement with expectations from reconnection.

[12] Finally, a plasma depletion layer (PDL) was observed. Going from the magnetosheath proper (after 15:15 UT) to the PDL next to the magnetopause the density and parallel temperature drop by 30% while the magnetic field strength increases by 30%. The Alfvén Mach number (based on the tangential flow) is >1 in the magnetosheath proper, but falls close to or slightly below unity in the PDL.

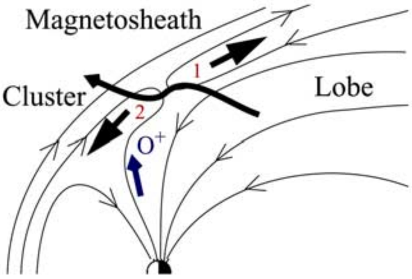

Figure 3. The effective trajectory of Cluster through the high-latitude reconnecting MP. The X-line moved tailward past the spacecraft during the MP crossing.

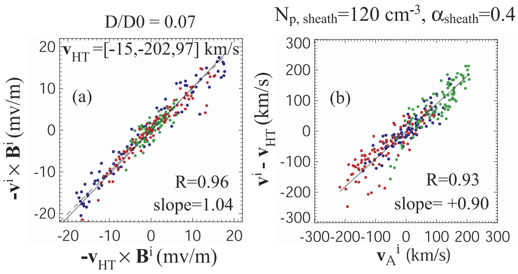

Figure 4. (a) deHoffmann-Teller and (b) Walén analyses of the MP for 14:57:25–15:03:06 UT interval in GSE. Blue, green, and red dots denote x, y, and z components.

3.4. Auroral Proton Emissions Expected From Jets

[13] To predict the number of counts expected in the IMAGE SI12 instrument from the reconnection jets, we map the field-aligned ion energy flux in the jets to the ionosphere. Assuming that any potential drop along the magnetic field between Cluster and the ionosphere is much smaller than the mean ion energy (of ~1 keV), the energy flux at the ionosphere is simply the energy flux per steradian in the loss cone at the Cluster altitude multiplied by π. The energy flux in the ionosphere is then converted to SI12 counts using the procedure of *Gérard et al.* [2001]. The mean energy of the sunward enhanced and downward reconnection jets (14:56:10–15:03:52 UT) varies between 550 eV and 2.8 keV, with an average of 970 eV. The energy flux varies between 1×10^{10} and 5×10^{11} eVs^{-1} cm^{-2} ster^{-1} with an average value of 1.3×10^{11} eVs^{-1} cm^{-2} ster^{-1}. These translate to 2–80 expected SI12 counts, with an average of 19.5 counts. These values are comparable to the SI12 counts in the spot (Figure 1d).

3.5. Mapping the MP Jets to the Ionosphere

[14] We next determine whether the jets are magnetically linked to the proton spot. The mapping is done using the Tsyganenko (T-89, T-96 and T-01) models [*Tsyganenko*, 2002, and references therein]. First, an optimal field model (and input solar wind pressure) is selected based on the comparison between the model field and the actual measured field in the magnetosphere next to the MP (at 14:55 UT). Figure 5b shows that if the measured solar wind pressure (~ 15 nPa) is used, the measured field ([88, −13, −138] nT in GSM) is much stronger and less steep than the T-01 model field ([38, −4, −128] nT) at the Cluster location. However, the agreement is greatly improved if the solar wind pressure is assumed to be twice the actual value. With a pressure of 33 nPa, the T-01 model field [90, −4, −137] nT agrees with the measured field to within 2% in magnitude and 3° in angle. The T-96 model produces similar results, but T-89, which has no solar wind dependency, cannot be made to match the measured field.

[15] Figure 2 shows the ionospheric footprints of the Cluster MP location using the T-89, T-96 and T-01 models with the measured (open squares) as well as the exaggerated (solid squares) solar wind pressures. The red, green, and blue contours in Figure 2b indicate the intensity levels corresponding to 33% (15 counts), 10% (5 counts) and 5% (2 counts) of the peak intensity (45 counts) of the spot at

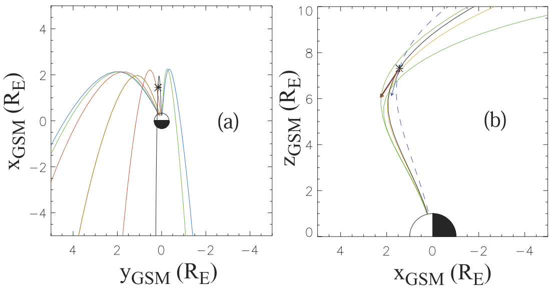

Figure 5. (a) Field lines starting from the proton spot in Figure 2b using T-01 with exaggerated (33 nPa) solar wind pressure. Black field line connects Cluster to the ionosphere. (b) Field lines linking Cluster to the ionosphere from T-01 using the exaggerated 33 nPa (black solid) and measured 15 nPa (blue dashed) solar wind pressures. Arrows represent field vectors at the Cluster location from actual measurements (red), T-01 with 33 nPa (black) and 15 nPa (blue) solar wind pressure.

14:58:56 UT. The T-96 and T-01 footprints with exaggerated solar wind pressure (solid white and orange squares) lie within the 10% (green) contour, whereas footprints of the T-89 and T-96 and T-01 models with measured solar wind pressure lie further from spot, especially in latitude. From this comparison, it is concluded that the T-01 and T-96 models with exaggerated pressure (33 nPa), which provide good agreement with the Cluster measured field, also yield reasonable mapping from the magnetopause to the ionosphere.

3.6. Mapping the Proton Spot to the Magnetopause

[16] Using the T-01 model with 33 nPa solar wind pressure, the proton spot is mapped out to the MP to obtain an estimate of the extent of the X-line. Figure 5a shows field lines originating from 7 points taken along the white line in Figure 2b that cuts through the center of the spot. The orange field line originates from the center of the spot. The red, green, and blue field lines originate from the contour lines of the same colors corresponding to 15, 5, and 2 SI12 counts, respectively. At the Cluster x_{GSM} location (of 1.6 R_E), the blue, green, red field line pairs span 3.9 R_E, 3.6 R_E, and 1.9 R_E in y_{GSM}, respectively. These values are estimates of the X-line extent since Cluster actually encountered an X-line at x_{GSM} = 1.6 R_E which oriented approximately in the y_{GSM} direction (inferred from the 175° shear). Since the 5-count level is statistically significant, a conservative estimate of the X-line is 3.6 R_E. This value should be considered a lower bound of the X-line length because the X-line may extend into lower magnetic shear regions from which the precipitations may not produce measurable SI12 fluxes.

4. Summary and Discussions

[17] 1. An event is reported where under northward IMF and high solar wind pressure conditions, a proton spot poleward of the dayside oval and tailward of cusp reconnection were simultaneously observed. The ion energy fluxes in the reconnection jets are sufficient in creating the observed proton emission and the jets are mapped to the vicinity of the proton spot, thus confirming the high-latitude reconnection source of the spot.

[18] 2. Cluster encountered the passage of an X-line. The evidence consists of (a) plasma jet reversal and (b) energetic O^+ present in the sunward jet but absent in the tailward jet consistent with a topological change. Thus at an instant in time, Cluster detected the precise location of the reconnection site. The magnetic fields were nearly anti-parallel (∼175°) at the Cluster location.

[19] 3. It is not possible to determine from in-situ measurements whether reconnection was also occurring at other high-latitude MP locations where the magnetic shear is smaller. However, using T-01 to map the area of the proton spot to the Cluster MP location results in an X-line of at least 3.6 R_E in y_{GSM}.

[20] 4. A depletion layer was observed next to the MP. The Alfvén Mach number was ∼2 in the magnetosheath proper but reduced to slightly below unity in the PDL. This feature is in agreement with the suggestion by *Fuselier et al.* [2000] that the high-latitude magnetosheath flow next to the MP may be sub-Alfvénic due to the presence of a PDL, in a region where gas dynamic models (without a PDL) would predict super-Alfvénic flows. This proposal was made to account for the inference of stable X-line at the high-latitude MP. The stability of the X-line cannot be confirmed from the present brief crossing of the MP.

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T. D. Phan, SSL, UC Berkeley, CA 94720, USA. (phan@ssl.berkeley.edu)