Retreat and reformation of X-line during quasi-continuous tailward-of-the-cusp reconnection under northward IMF

H. Hasegawa,[1] A. Retinò,[2] A. Vaivads,[3] Y. Khotyaintsev,[3] R. Nakamura,[2] T. Takada,[1] Y. Miyashita,[1] H. Rème,[4] and E. A. Lucek[5]

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[1] We present observations on 19–20 November 2006 by the Cluster spacecraft that were skimming the high-latitude dusk-flank magnetopause, which are consistent with more than one reconnection X-line present on the tailward side of the cusp under northward IMF. Evidence of quasi-continuous reconnection over 16 hours exists in the form of Alfvénic acceleration of magnetosheath ions found almost always when either of the satellites traversed the boundary. The data indicate that a dominant X-line was sunward of Cluster for most of the time, but ion velocity distributions consisting of two magnetosheath populations demonstrate that for part of the time, more than one X-line existed. Further, the motion of reconnected field lines shows that some X-line(s) retreated tailward. It is inferred that following the X-line retreat, another X-line reformed sunward of Cluster, leading to multiple X-lines. **Citation:** Hasegawa, H., A. Retinò, A. Vaivads, Y. Khotyaintsev, R. Nakamura, T. Takada, Y. Miyashita, H. Rème, and E. A. Lucek (2008), Retreat and reformation of X-line during quasi-continuous tailward-of-the-cusp reconnection under northward IMF, *Geophys. Res. Lett.*, *35*, L15104, doi:10.1029/2008GL034767.

1. Introduction

[2] It has been demonstrated that magnetic reconnection occurs at various places in the solar system, such as at the magnetopause [e.g., *Sonnerup et al.*, 1987; *Gosling et al.*, 1991] and in the solar wind [e.g., *Gosling et al.*, 2007]. Recent observations show that reconnection is not intrinsically intermittent [*Phan et al.*, 2006]. It was inferred from observations of proton aurora in the dayside polar ionosphere, the remote signature of magnetopause reconnection tailward of the cusp [*Frey et al.*, 2003], as well as from observations at the low-latitude magnetopause [*Gosling et al.*, 1986, and references therein] that reconnection can be continuous for hours. This conjecture has been confirmed by in situ measurements at the magnetopause both equatorward and poleward of the cusp [*Phan et al.*, 2004; *Retinò et al.*, 2005] and in the solar wind [*Gosling et al.*, 2007].

[3] Continuous reconnection near the subsolar magnetopause appears to involve a single and quasi-stationary X-line [*Phan et al.*, 2004]. However, little is known about whether a single X-line sits still and remains active for an extended period of time, or X-line retreats and then another X-line reforms near the original reconnection site, at the high-latitude or flank magnetopause where significant flow tangential to the boundary exists on the magnetosheath side (see, however, a related work by *Fuselier et al.* [2000]).

[4] In this letter, we report observations by the Cluster spacecraft in and around the high-latitude dusk-flank magnetopause, which show that at least for part of the time, more than one X-line existed in association with quasi-continuous tailward-of-the-cusp reconnection under northward IMF. Further, the observations suggest that the multiple X-lines resulted from creation of new X-line following tailward retreat of an X-line.

2. Observations and Analysis

[5] We analyze Cluster data taken from 1030 UT, 19 November 2006 to 0400 UT, 20 November 2006, when the satellites were skimming the dusk-flank magnetopause from $X \sim -5$ to $+1$ R_E in the southern hemisphere. Data from Cluster-1 (C1), C3, and C4 are used for which ion velocity data having quality sufficient for reconnection jet identification are available. The separation between C1 and C3 was ~ 1 R_E, and C1 was on the magnetosphere side of C3 (as is evident from Figure 1). C3 and C4 were closer together but at a distance of >1000 km from each other (Figure S1 in auxiliary material[1]).

[6] Figure 1 shows an overview of data in GSM from the ACE spacecraft at L1 and Geotail satellite immediately upstream of the bow shock as well as from Cluster. The ACE and Geotail data are time-shifted by 64 min and 5 min, respectively, taking the solar-wind propagation time into account. The intensity of the IMF remained approximately constant (~ 8 nT) (Figure 1a). The IMF clock angle (Figure 1b), defined by $\tan^{-1}(B_y/B_z)$, shows that the IMF was persistently northward and dawnward during the interval after 1100 UT. For this IMF orientation, an anti-parallel reconnection site is expected to be at the duskside magnetopause in the southern hemisphere.

[7] Under this relatively stable IMF condition, Cluster traversed the magnetopause repeatedly, which is best characterized by changes in the B_x polarity (Figure 1g) and jumps in the density (Figure 1c). Many of inbound and outbound crossings appear to correlate with modest decreases and increases, respectively, of the solar wind density (Figure 1c). Since Cluster was in the southern part of the dusk-flank magnetosphere, $B_x < 0$ and $B_y > 0$ on the

[1]Institute of Space and Astronautical Science, JAXA, Sagamihara, Kanagawa, Japan.
[2]Space Research Institute, Austrian Academy of Science, Graz, Austria.
[3]Swedish Institute of Space Physics, Uppsala, Sweden.
[4]Centre d'Etude Spatiale des Rayonnements, Toulouse, France.
[5]Blackett Laboratory, Imperial College, London, UK.

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[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2008gl034767. Other auxiliary material files are in the HTML.

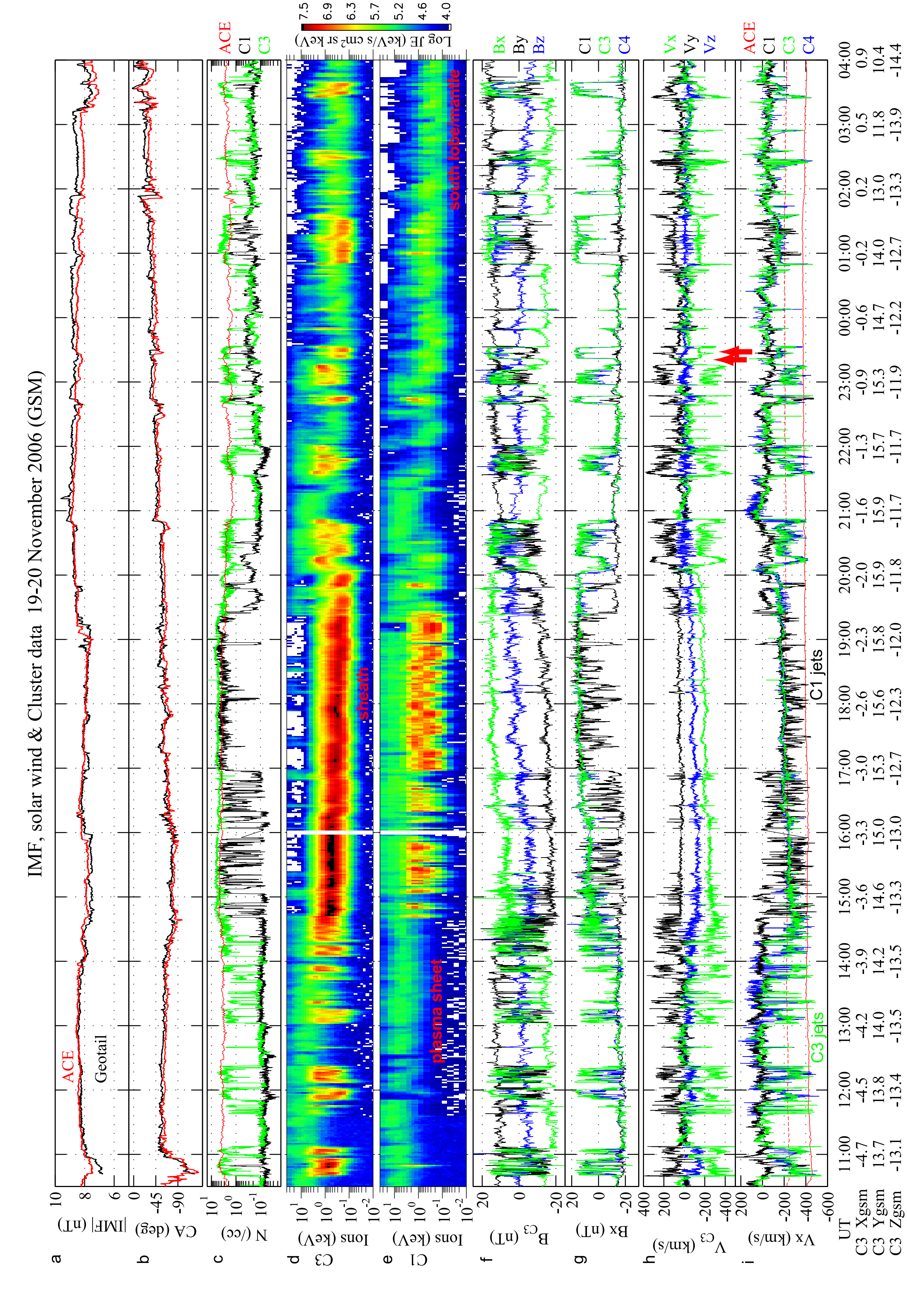
IMF, solar wind & Cluster data 19-20 November 2006 (GSM)
ACE
Geotail
|IMF| (nT)
CA (deg)
N (/cc)
C3 Ions (keV)
C1 Ions (keV)
Log JE (keV/s cm² sr keV)
sheath
plasma sheet
south lobe/mantle
B_C3 (nT)
Bx By Bz
Bx (nT)
C1 C3 C4
V_C3 (km/s)
Vx Vy Vz
Vx (km/s)
C3 jets
C1 jets
UT
C3 Xgsm
C3 Ygsm
C3 Zgsm

Figure 1

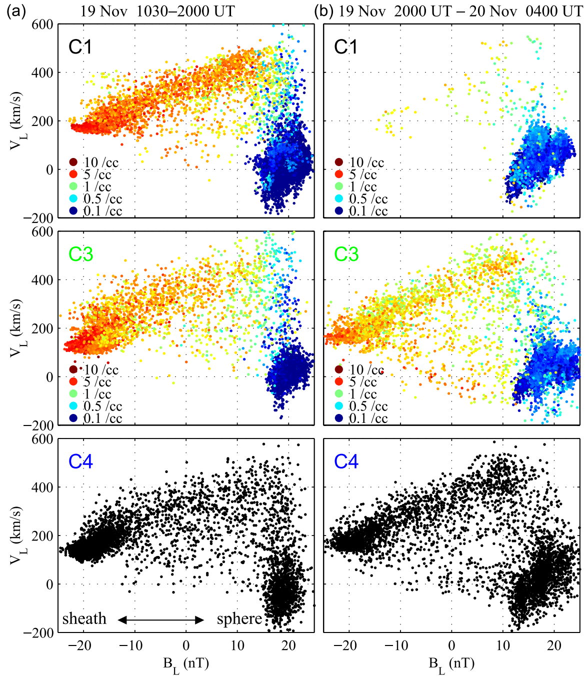

Figure 2. Scatter plots of the L components of the ion velocity and magnetic field for intervals (a) 1030–2000 UT on 19 Nov. 2006, and (b) 2000 UT, 19 Nov.–0400 UT, 20 Nov. Colors of the data points show ion density in the top two panels.

magnetospheric side, while the magnetosheath field sampled by C3 for 1445–2000 UT was sunward and dawnward (Figure 1f). A southward field component, seen for 1445–1700 UT, is probably due to draping of the IMF over the magnetosphere (note that the first in situ observation of reconnection tailward of the cusp was made when the local magnetosheath field had a southward component [*Gosling et al.*, 1991]). The magnetic shear across the local magnetopause was within 150–175° over the entire period (Data Set S1 in auxiliary material). Ion energy-time spectrograms (Figures 1d and 1e) show that, when within the magnetosphere, Cluster was in the plasma sheet, where the energy flux peak is at ~10 keV, for the earlier interval (until ~2200 UT) while afterward it was in the southern lobe/mantle where the peak is below 1 keV, consistent with the fact that Cluster was generally moving southward, i.e., toward higher latitudes (Figure S1 in auxiliary material).

[8] Striking in this event is that fast tailward and duskward flows, approximately along the local magnetopause, were found almost always when Cluster was in or near the magnetopause (Figure 1h). Figure 1i shows that $|V_x|$ in these flows (300–500 km/s) was significantly higher than in the magnetosheath (~200 km/s), suggesting that Cluster saw reconnection jets on the tailward side of an X-line. Figure 2 shows scatter plots of the L components of the ion velocity and magnetic field for the entire period, with ion density denoted by color for C1 and C3 which provide reliable density measurements as well. Here L is the maximum variance direction of the magnetic field, determined by minimum variance analysis with sliding window, and is defined positive tailward and duskward. The reconnecting field component can be represented by the field in this direction, tangential to the local magnetopause. We note a distinct positive and linear correlation between V_L and B_L (in the upper part of the panels) for a majority of data points sampled in the magnetopause ($-20 < B_L < 15$ nT). As expected for magnetopause reconnection, the V_L increase $\geq$300 km/s, from ~150 km/s in the magnetosheath to $\geq$450 km/s on the magnetosphere side, is comparable to the change in the Alfvén velocity (~360 km/s) across the magnetopause, based on the magnetosheath density 6 cm^{-3} and reconnecting field B_L ~20 nT. Consistent with entry of magnetosheath plasma along reconnected field lines, the density is high (>1 cm^{-3}) throughout the entire magnetopause current layer. We thus conclude that Cluster detected reconnection jet almost always when crossing the magnetopause. Since reconnection equatorward of the cusp cannot lead to the tailward acceleration (positive V_L increase) at the Cluster location, the jets would be due to reconnection tailward of the cusp. The results indicate that tailward-of-the-cusp reconnection was almost always ongoing over the analyzed interval (~16 hours), although we cannot exclude the possibility that reconnection ceased when neither of the spacecraft was in the magnetopause (we find significant high-speed jets as long as 30% of the entire interval and >50% of time for 1400–1500 UT).

[9] Interestingly, the C3 and C4 scatter plots for the later interval (Figure 2b) show not only positive but also weak negative correlations between V_L and B_L (especially for points characterized by higher densities, in the lower part of the panels). It suggests that the satellites sometimes saw jets on the sunward side of X-line. This is confirmed by testing the Walén relation [*Sonnerup et al.*, 1987] for a pair of adjacent magnetopause crossings (Figure 3). The positive and close-to-unity slope is consistent with C3 being tailward of an X-line where the field component B_N normal to the magnetopause is negative, while the significant negative slope is consistent with C3 being sunward where B_N is positive (Figure 4).

[10] We note that the deHoffmann-Teller (HT) velocity [*Sonnerup et al.*, 1987] for the negative-slope interval, when a jet sunward of an X-line was detected, has a tailward and duskward component (Figure 3b). Since this HT velocity would represent the motion of field lines sunward of the associated X-line, it is inferred that the X-line was traveling tailward at an even higher speed. Note also that the jet

Figure 1. Observations by Cluster in and around the high-latitude dusk-flank magnetopause and by ACE and Geotail in the upstream solar wind on 19–20 Nov. 2006. (a) Magnitude and (b) clock angle of the IMF seen by ACE and Geotail. (c) Ion density at ACE, C1, and C3, (d, e) energy-time spectrograms for tailward-streaming ions from CIS/HIA onboard C3 and C1, (f) three GSM components of the magnetic field at C3, (g) B_x at C1, C3, and C4 whose polarity change can be used as a proxy of magnetopause crossing, (h) three GSM components of the HIA ion flow velocity from C3, and (i) V_x seen by ACE, C1(CIS/HIA), C3(CIS/HIA), and C4(CIS/CODIF). The red dashed line represents 55% of the solar wind V_x and roughly matches V_x at Cluster in the magnetosheath. Red arrows in Figure 1h mark the intervals for the Walén test (Figure 3).

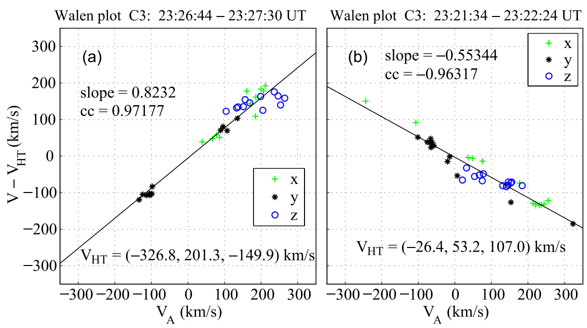

Figure 3. Walén relations using C3 data for intervals (a) 2326:44-2327:30 UT and (b) 2321:34–2322:24 UT.

consistent with C3 being tailward of an X-line was detected only a few minutes later (Figure 3a). The HT velocity (412 km/s) for this jet, having a significant tailward and duskward component, is much higher than the Alfvén speed in the ambient magnetosheath (260 km/s). This fact indicates that the change in sign of the Walén slope within a few minutes was not due to a tailward-then-sunward motion of a single X-line present near the spacecraft, because if an X-line was near Cluster and was moving sunward, the HT velocity tailward of the X-line should have been less than the magnetosheath Alfvén speed (note that in the X-line rest frame, the HT speed in reconnection jet is at most the Alfvén speed). The data thus seem to suggest that at this time, another X-line was on the sunward side of C3, in addition to the tailward-retreating X-line on the tailward side, i.e., suggest the presence of more than one X-line or a process of X-line reformation (see Data Set S2 in auxiliary material, for further support for the X-line retreat).

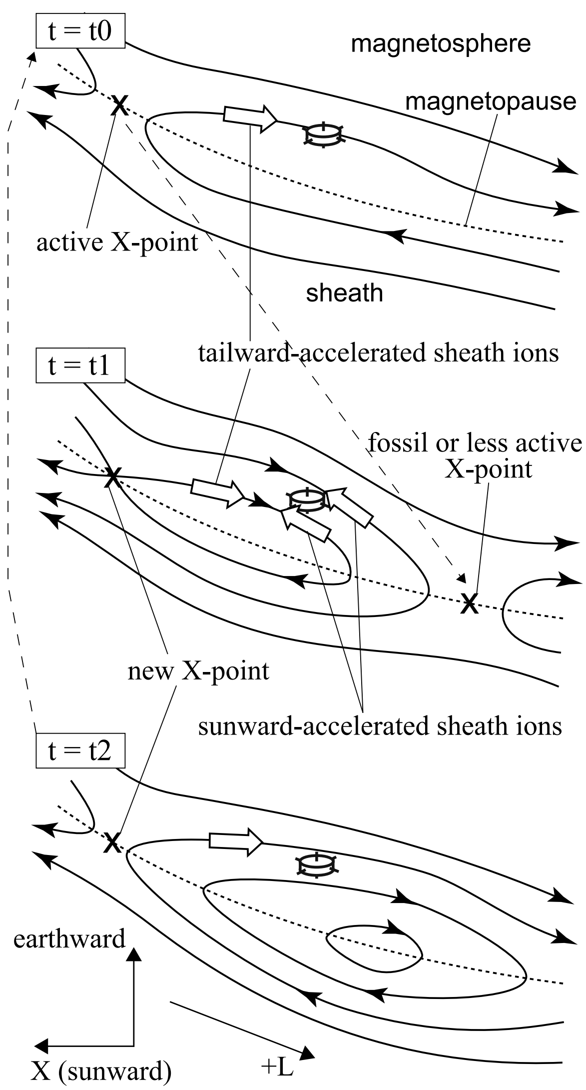

Figure 4. Schematic of magnetic field lines around Cluster near the dusk-flank magnetopause. Tailward retreat of X-line, followed by formation of new X-line, can explain the present observations.

[11] Ion velocity distributions consistent with the existence of multiple X-lines are obtained in the lobe/mantle ($B_x < 0$) region (Figure 5). Figure 5b shows two distinct magnetosheath-like ion populations, one at a field-aligned velocity of 500 km/s and another at −50 km/s. They are both rather dense, and thus must be from recent entry to the magnetosphere. As depicted in the middle sketch in Figure 4, we interpret the former as magnetosheath ions accelerated tailward on the tailward side of an X-line that was sunward of C1, and the latter as those accelerated sunward on the sunward side of another X-line that was then tailward of C1 (see Figures S2 and S3 in auxiliary material, for demonstration of not-infrequent occurrence of the double-component ion distribution as evidence of multiple X-lines). The negative field-aligned velocity ($V_x > 0$) of the latter as well as V_L being occasionally negative ($V_x > 0$) in the central part of the magnetopause current layer ($|B_L| < 10$ nT in Figure 2b) is compatible with the fact that the Alfvén Mach number in the magnetosheath was ∼1 (<2) so that sunward flow can result on the sunward side of X-line [*Fuselier et al.*, 2000; *Twitty et al.*, 2004, and references therein].

3. Discussion

[12] We have shown a Cluster event consistent with tailward-of-the-cusp reconnection being quasi-continuous over 16 hours under northward IMF, namely, for approximately antiparallel field configurations. Our observations show that a primary X-line existed sunward of Cluster, perhaps near but tailward of the cusp, for most of the time, but suggest also that at least for part of the time, multiple X-lines existed and some X-line retreated tailward and was tailward of Cluster. These observations (Figures 2b, 3, and 5)

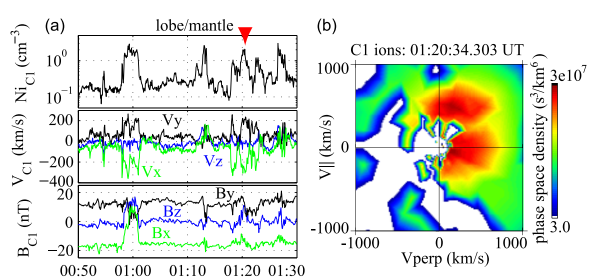

Figure 5. (a) Data from CIS/HIA and FGM onboard C1 for 0050–0130 UT on 20 Nov. (b) Ion velocity distribution from CIS/HIA taken at the time marked in Figure 5a by red triangle.

can be explained by a model depicted in Figure 4, in which the X-line retreat is followed by creation of new X-line near the original site. We note that the reconnection process in this model is similar to the way reconnection occurs in the course of the generation of flux transfer events (FTEs) in a global MHD simulation under the presence of dipole tilt [*Raeder*, 2006]; reconnection looks continuous in a global sense and tangential plasma flow present in the magnetosheath appears to be the key to the X-line retreat and creation of multiple X-lines.

[13] We point out that FTE-like signatures were often seen in the present event, e.g., at 0113 UT in Figure 5a. These FTEs as well as partial crossings of the magnetopause, as seen by C1 for 1500–1900 UT (Figure 1g), may be due to swellings of the magnetopause boundary layer resulting from temporal variation in the reconnection rate [*Phan et al.*, 2004]. We however infer that some of those features in this particular event were caused by the tailward motion of magnetic islands or flux ropes, expected to form in our model (Figure 4). In fact, some data points in Figure 2 around $B_L \sim 0$ nT and $V_L \sim 200$ km/s cannot be categorized into two classes, one with the positive correlation associated with jets tailward of X-line and another with the negative correlation associated with sunward jets, and may be consistent with being sampled within flux ropes. These meso- and micro-scale aspects of the present event will further be studied in future.

[14] **Acknowledgments.** We thank Hans Eichelberger for producing the magnetic field data from Cluster/FGM, and T. Nagai for permission of the use of Geotail/MGF magnetic field data. The ACE data were provided via the CDAWeb.

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H. Hasegawa, Y. Miyashita, and T. Takada, Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan. (hase@stp.isas.jaxa.jp)

Y. Khotyaintsev and A. Vaivads, Swedish Institute of Space Physics, Uppsala SE-75121, Sweden.

E. A. Lucek, Blackett Laboratory, Imperial College, Prince Consort Road, London SW7 2BZ, UK.

R. Nakamura and A. Retinò, Space Research Institute, Austrian Academy of Science, Schmiedlstr. 6, A-8042 Graz, Austria.

H. Rème, Centre d'Etude Spatiale des Rayonnements, 9 Avenue du Colonel Roche, B.P. 4346, F-31028 Toulouse, France.