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[1] We present results of a favorable conjunction where the equatorial spacecraft (TC-1) of the Double Star mission exits the dayside magnetopause near the equator, while Cluster is inbound, near the southern cusp. This configuration makes it possible to compare observations of the magnetopause, around the same magnetic local time but at different latitudes. In this paper, we report on the general properties of the magnetosheath plasma at the two latitudes: unlike predictions from gasdynamic modeling, the density is found lower near the nose of the magnetopause than further downstream. Then, we present three interesting events. First, an FTE is observed at TC-1 and not at Cluster; we discuss the implications this has on the evolution of FTEs and on the size of the reconnection site. Then, a structure observed at both spacecraft is interpreted as a bulge progressing along the magnetopause. It is not clear whether this bulge is actually the remnant of an FTE or a running pulse that makes Cluster sense the reconnection layer. In any case, a rotational discontinuity is observed within it. At last, a northward turning of the magnetosheath magnetic field is observed at TC-1 and a reverse FTE is subsequently seen at Cluster, suggesting that magnetic reconnection is very fast to set up following a change in the IMF orientation.

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1. Introduction

1.1. Magnetosheath Plasma

[2] As it approaches the Earth's environment, the solar wind first interacts with the foreshock region [*Formisano and Amata*, 1976; *Fairfield et al.*, 1990] and with the bow shock where it gets compressed. For a high-Mach number flow, as it is most of the time the case, hydrodynamic modeling shows that the compression ratio is ~4 near the subsolar point and that the compressed magnetosheath plasma tends to expand as it flows along the magnetosphere to reach values of ~2 at higher latitudes [*Spreiter et al.*, 1966]. This was partly verified observationally by *Spreiter and Alksne* [1968] and by *Formisano et al.* [1973] near the bow shock, although latter authors concluded that "the study of the density jump has been found to be very difficult as it depends strongly on many other parameters." The parameters the authors mention are mainly the upstream Mach number and the orientation of the IMF with respect to the bow shock.

[3] Of course, the model by *Spreiter et al.* [1966] and even the later attempt to improve it [*Spreiter and Stahara*, 1980] being gasdynamic models, the interactions between the magnetosheath plasma and magnetic field are not well described. As far as the plasma flow and density are concerned, significant differences between model predictions and satellite observations were reported [*Šafránková et al.*, 2004; *Němeček et al.*, 2000]. This turned out to be particularly true when the magnetosheath plasma approaches the magnetopause. The combined effects of both diversion of the flow around the magnetopause and the pileup effect of the magnetic field, which tends to decrease the plasma density [*Farrugia et al.*, 1998], are not taken into account in gasdynamic models. This effect was added by *Zwan and Wolf* [1976] in their model, which well describes the plasma depletion layer in the magnetosheath, very close to the subsolar magnetopause.

[4] Recently, *Longmore et al.* [2005] carried out a statistical survey of the high- and low-latitude magnetosheath using the Cluster spacecraft. One of their main conclusions was that they observe a deceleration of the magnetosheath flow not only near the nose of the magnetopause but also close to the magnetopause at high latitudes.

1.2. Magnetic Reconnection at the Magnetopause

[5] Magnetic reconnection at the magnetopause is thought to be the main process allowing the magnetosheath plasma to enter the Earth's magnetosphere. In satellite data,

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magnetic reconnection has several signatures, though not always observed simultaneously.

[6] Bipolar signatures in the magnetic component normal to the nominal magnetopause have first been observed and interpreted in terms of magnetic reconnection by *Russell and Elphic* [1978, 1979]. Flux transfer events (FTEs), as they were named, are the signature of newly reconnected field lines passing by a satellite at or near the Earth's magnetopause. FTEs have been observed between the two polar cusps, either in the magnetosheath or in the magnetosphere, when the interplanetary magnetic field (IMF) points southward [*Rijnbeek et al.*, 1984]. The polarity of these magnetic structures depends on the hemisphere or more precisely on the location of the spacecraft with respect to the reconnection site. As shown statistically by *Berchem and Russell* [1984] and *Rijnbeek et al.* [1984], north of the reconnection site, a (+, −) polarity is observed, i.e., a positive deflection of B_N followed by a negative deflection (B_N being the magnetic field component normal to the magnetopause). On the other hand, south of the reconnection site, the opposite polarity (−, +) is observed. From the particle point of view, it has been shown and observed that FTEs actually correspond to entry of magnetosheath particles into the magnetosphere [*Paschmann et al.*, 1982; *Southwood et al.*, 1988]. The plasma within FTEs displays magnetosheath characteristics: high fluxes of keV ions, similar density, etc. As a matter of fact, it is a mixture of magnetospheric and magnetosheath plasma. The distribution functions show that injected magnetosheath particles are accelerated along the magnetic field as expected for magnetic reconnection [*Daly et al.*, 1981; *Thomsen et al.*, 1987].

[7] However, some clear reconnection events have been reported where plasma jets are observed together with positive Walen test [*Khrabrov and Sonnerup*, 1997], indicative of a rotational discontinuity, and no FTE-type signature [*Paschmann et al.*, 1979]. Also, one should bear in mind that reconnection events may have a complex 3-D structure, far more complicated that the simple 2-D view of rolled magnetic field lines [*Louarn et al.*, 2004].

[8] From an observational point of view, magnetic reconnection at the magnetopause has been mainly recorded by single-spacecraft missions at a given location. Recently, the Cluster mission [*Escoubet et al.*, 2001] has improved a lot our understanding of magnetic reconnection, at small or larger scale, and the associated dynamics of newly open flux tubes. The continuous nature of magnetic reconnection has been highlighted [*Retinò et al.*, 2005; *Bavassano-Cattaneo et al.*, 2006] for instance, while its impulsive behavior has been also studied in 3-D [*Marchaudon et al.*, 2004; *Fear et al.*, 2005; *Wang et al.*, 2005, 2006]. Simultaneous or consecutive observations of reconnection events at different places of the magnetopause or observations of the evolution of a reconnected flux tube are much rarer. *Kawano and Russell* [2005] performed a statistical study of 10 years of ISEE 1 and 2 data, although they could not fully resolved the direction of motion of the FTEs with only two spacecraft. *Marchaudon et al.* [2005] and *Dunlop et al.* [2005] for instance used the 3-D capability of Cluster in addition to the Double Star spacecraft to determine the motion of the FTEs. This motion turned out to be in very good agreement with the *Cooling et al.* [2001] model of open flux tube motion [*Dunlop et al.*, 2005].

[9] At last, it should be mentioned that *Sibeck* [1990] proposed an alternative explanation for bipolar signatures in magnetic data: some of them would be the consequence of solar wind pressure pulses. According to the author, pressure pulses would yield running troughs and bulges along the magnetopause, signature of which would resemble and therefore sometimes be confused with that of FTEs.

2. Observations

[10] In February and March 2004, shortly after its launch, the equatorial Double Star spacecraft TC-1 [*Liu et al.*, 2005], whose apogee was then in the dayside near the magnetopause, found itself in good position to be in conjunction with Cluster [*Escoubet et al.*, 2001], then crossing each of the cusps once per orbit at high altitude (~10–12 R_E). These conjunctions are highly favorable to study the solar wind plasma entry in the Earth's magnetosphere.

[11] On 25 February 2004, TC-1 and Cluster were both in the southern hemisphere, near the magnetic noon meridian (Figure 1). We shall look in this study at the time interval ~0300–0400 UT, over which TC-1 exits the magnetosphere near the subsolar point, whereas meanwhile, Cluster, first in the magnetosheath, approaches and crosses the magnetopause to enter the magnetosphere, near and slightly poleward of the Southern Hemisphere's cusp. Note that the separations between the Cluster spacecraft were small at that time: 600 km at most (between SC1 and SC4). Separation between SC2 and SC3 was about 200 km.

[12] Among the instruments on board Cluster and TC-1, we have used the hot ion analyzer (HIA) [*Rème et al.*, 2001, 2005], the fluxgate magnetometer (FGM) [*Balogh et al.*, 2001; *Carr et al.*, 2005], and the plasma electron and current experiment (PEACE) [*Johnstone et al.*, 1997; *Fazakerley et al.*, 2005].

2.1. ACE Data and Propagation Time

[13] Solar wind parameters and the interplanetary magnetic field (IMF) are monitored respectively by the SWEPAM and MAG instruments onboard the Advanced Composition Explorer (ACE) spacecraft. Before looking at the data, we need to evaluate the lag time due to solar wind propagation from ACE (orbiting at 223 R_E away from the Earth) to the magnetopause. We have displayed in Figure 2 the IMF clock angle at ACE and Cluster (top) and ACE and TC-1 (bottom). Note that the adjustment was done for period of good correlation, i.e., in the magnetosheath. The time intervals chosen for adjusting ACE to TC-1 and ACE to Cluster (shown by red rectangles in Figure 2) are therefore not the same. Figure 2 shows the superimposition of the IMF clock angle (θ_{IMF}) recorded at Cluster (red), TC-1 (blue), and at ACE (black). A lag time of 65 min has been applied to ACE data to match both TC-1 and Cluster data. In the case of Cluster, we can note that the IMF clock angle is conserved through the bow shock and in the magnetosheath as long as we deal with low latitudes, i.e., near the nose of the magnetopause. However, as the magnetosheath plasma flows along the flanks of the magnetosphere, it becomes more turbulent and therefore, magnetic field orientation deviates significantly from the IMF [e.g., *Retinò et al.*, 2005]. This is clearly observed at Cluster from about 0315 UT.

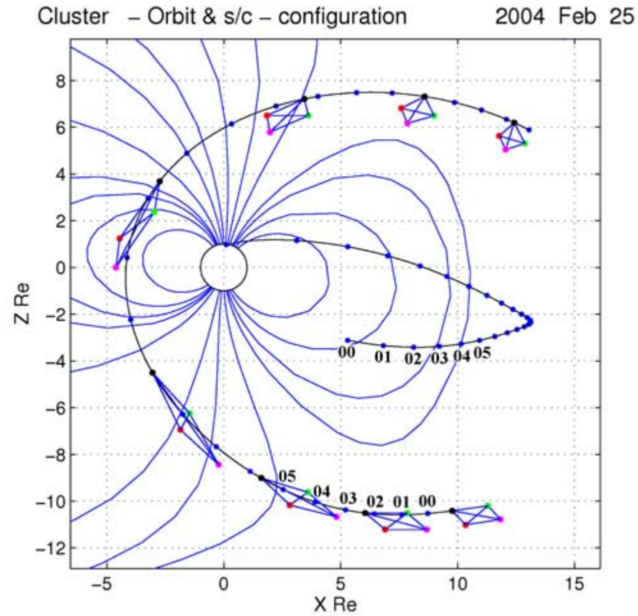

Figure 1. TC-1 and Cluster orbits on 25 February 2004 projected on a (X_{GSM}, Z_{GSM}) plane. Cluster (C1: black; C2: red; C3: green; C4 magenta) is inbound near the southern cusp, while TC-1 is outbound south of the equator.

[14] The ACE data shown in Figure 3 are thus lagged by 65 min. Figure 3 shows the three components of the IMF in GSM as well as the solar wind density and X component of the velocity. Let us note that given the locations of the spacecraft (TC-1 at $X_{GSM} \sim 10$ R_E; Cluster at $X_{GSM} \sim 6$ R_E), we expected to find different lag times. The same time lag at both Cluster and TC-1 may be explained by the combined effect of the deceleration of the magnetosheath flow near the nose of the magnetosphere and the draping of the magnetic field lines at higher latitude.

[15] The time intervals that we will look at are between 0300 and 0330 UT and around 0400 UT. For the former, the IMF was predominantly southward with X, Y, and Z components of (0, −2, −2) nT in GSM. These conditions should favor magnetic reconnection at the low-latitude magnetopause, i.e., between the two cusps. For the latter, a short-lived IMF turning from southward (−2 nT) to slightly northward (+0.5 nT) is observed. The solar wind density and velocity are $\sim$3.5 cm^{-3} and $\sim$370 km/s, respectively throughout the whole period of interest.

2.2. Overview of Double Star Data

[16] Figure 4 displays data from the HIA sensor (high-sensitivity side) and FGM on board TC-1 between 0230 UT and 0330 UT. Shown, from top to bottom, are an omnidirectional ion spectrogram, the ion density, the three components of the ion velocity in GSM, and the three components of the magnetic field in GSM. Before 0247 UT, HIA records high-energy (>10 keV) ions, which suggests that the spacecraft is on closed magnetic field lines, i.e., in the magnetosphere. From 0247 UT, HIA starts to pick up magnetosheath particles: high fluxes of keV ions along with increases of the density (up to $\sim$20 cm^{-3}) as well as the velocity ($\sim$100 km/s and up to $\sim$250 km/s at times). And after 0315 UT, TC-1 is out in the magnetosheath: the velocity and the density are rather stable around 100 km/s and 20–25 cm^{-3}, respectively. More interestingly for our study, TC-1 remains near the magnetopause from 0247 to 0315 UT. Observations by the HIA sensor (Figure 4) reveal several plasma accelerations (jets) associated to magnetosheath plasma encounters. Those

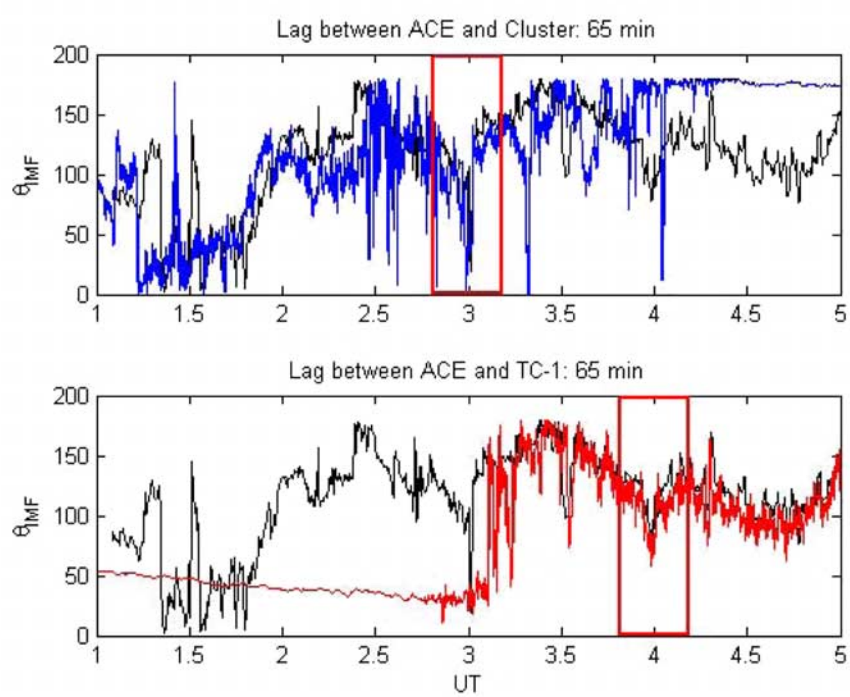

Figure 2. Lagged clock angle of the interplanetary magnetic field (IMF) measured by ACE (black) and clock angle of the magnetic field at Cluster (blue) and TC-1 (red).

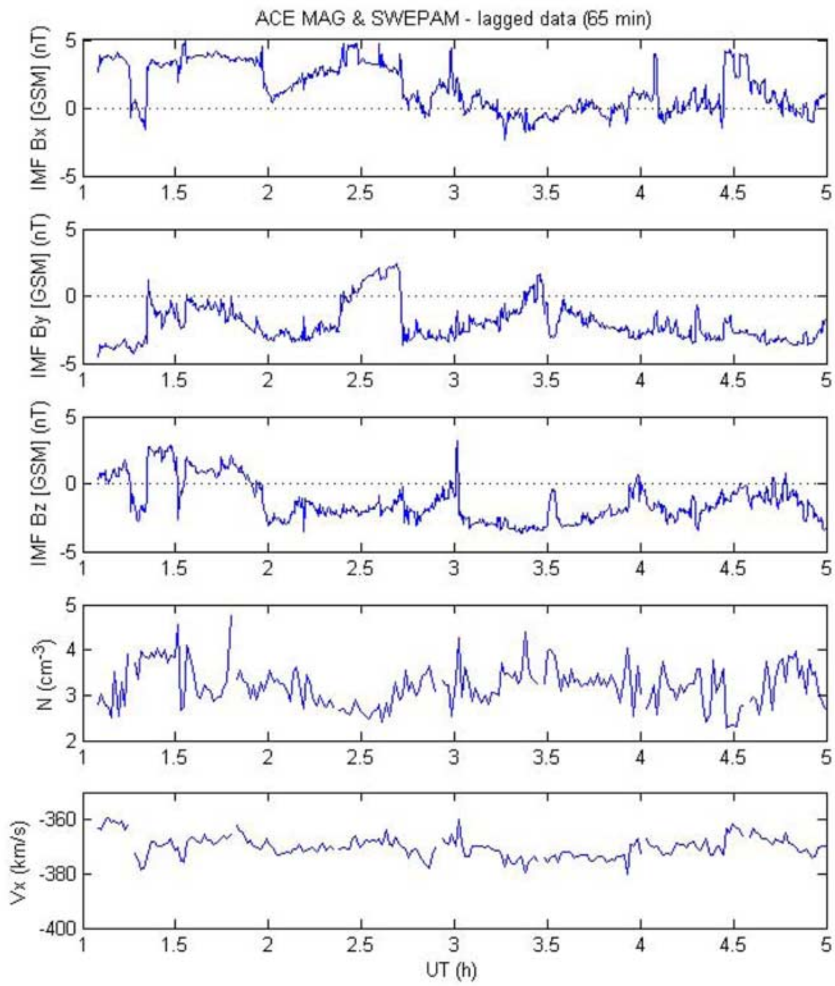

Figure 3. IMF and solar wind conditions measured by the ACE spacecraft. From top to bottom, the figure shows the three GSM components of the IMF (X, Y, and Z, respectively), the solar wind number density and the Sun-Earth component of the solar wind velocity. All data have been lagged by 65 mn.

jets of accelerated magnetosheath plasma (up to 250 km/s and mainly in the −Z and +Y direction in our case) are usually associated with magnetic reconnection [*Paschmann et al.*, 1979]. The magnetic shear between the magnetosheath and the magnetosphere is of the order of 100°, which is a priori not a very favorable condition for having anti-parallel reconnection.

[17] Figure 5 displays FGM data from TC-1 and the four Cluster spacecraft. Figures 5a, 5b, and 5c show respectively the Z, Y, and X components of the magnetic field in GSM. In order to have the magnetic field in the magnetopause frame, we have performed a minimum variance analysis (MVA) of the magnetic field [*Sonnerup and Cahill*, 1967; *Sonnerup and Scheible*, 1997], the result of which is displayed in the lower part of Figure 5. Figures 5d, 5e, and 5f show the L, M, and N components of the magnetic field recorded at TC-1 in blue and Cluster. Figure 5g displays the total magnetic field.

[18] For TC-1, the calculation of the LMN coordinates was done on the time interval 0305–0307 UT at TC-1. The GSM coordinates of the eigenvectors are given below:

N 0.8731 −0.2911 −0.3911
M 0.1638 0.9307 −0.3271
L 0.4592 0.2215 0.8603

The eigenratio is 4.5–5 and remains stable, i.e., insensitive to the interval chosen for the analysis.

[19] Interestingly enough, in our case, only one of those jets seems to be associated with a bipolar signature in the magnetic field normal to the magnetopause (Figure 5f, blue curve) at 0308 UT. We shall refer to this FTE as event 1 in this paper (this event is marked by a yellow bar in Figure 5).

[20] Shortly after, at ∼0314 UT, there is a second strong signature in the magnetic field (referred to as event 2, marked by a green bar in Figure 5). In GSM coordinates

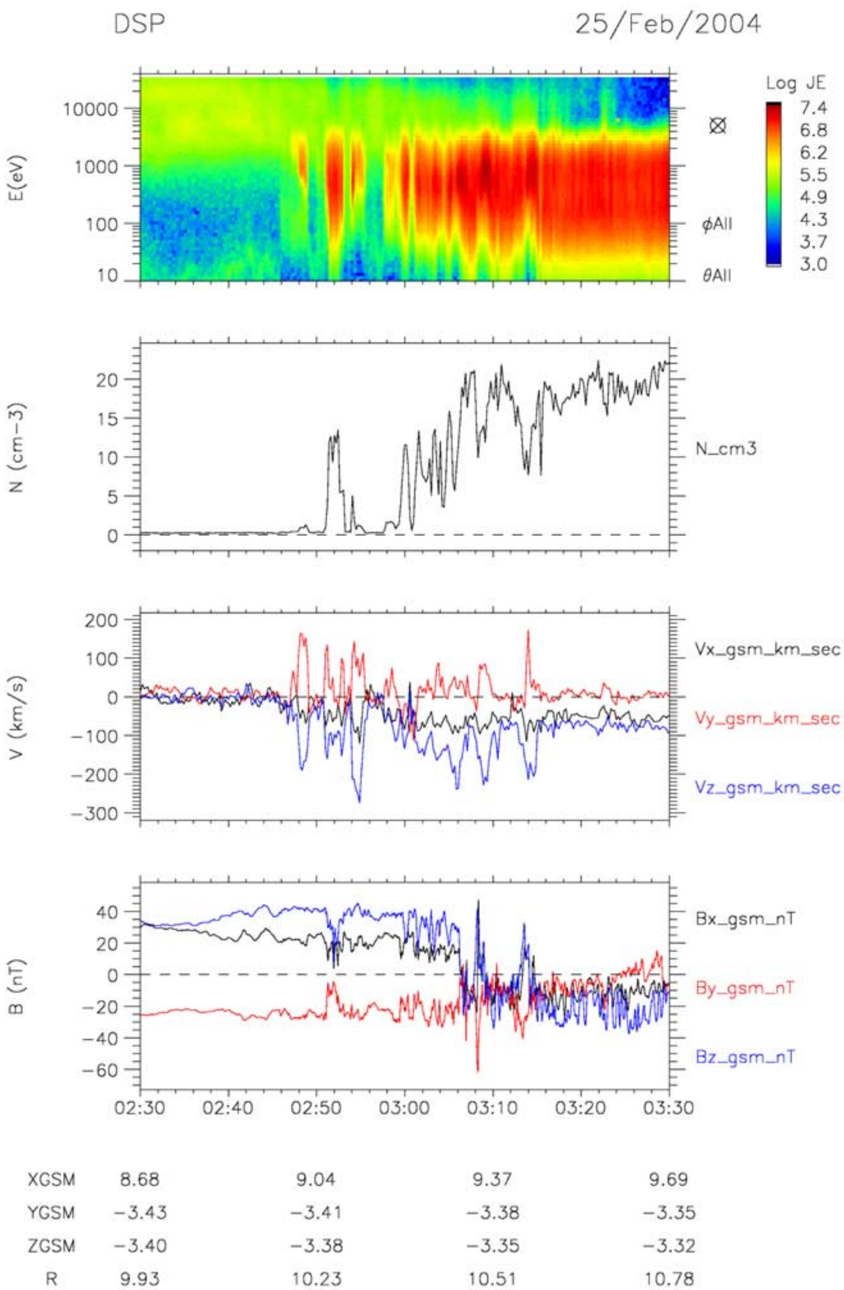

Figure 4. Hot ion analyzer (HIA) and fluxgate magnetometer (FGM) data recorded on board TC-1 between 0230 and 0330 UT. Shown from top to bottom are an energy-time spectrogram, the ion number density, the three GSM components of the plasma flow, and the three GSM components of the magnetic field.

(Figure 5), it looks very similar to the previous one: it exhibits an increase of the Z and X components from −10 to +30 nT and from −10 to +20 nT, respectively. But in LMN coordinates, although a tiny bipolar signature may be seen, it does not convincingly look like an FTE.

[21] At last, we shall look at a third event. Indeed, we shall see later that the northward turning of the magnetosheath field observed at ~0400 UT at TC-1 (blue curve in Figure 5a) and named event 3 has consequences in Cluster observations (event 3′: reverse FTE). Both event 3 and 3′ are marked by two red bars in Figure 5.

2.3. Overview of Cluster Data

[22] Figure 6 shows HIA and FGM data from Cluster SC1 from 0100 to 0500 UT. The format is the same as for TC-1 (Figure 4): ion energy spectrogram, density, velocity, and magnetic field, from top to bottom. As introduced previously, it can be clearly seen from ion data that Cluster is in the magnetosheath (high flux of keV ions) until ~0400 UT, time at which it crosses the magnetopause to enter the magnetosphere in the lobes (low flux of few hundred eV ions, very low density), a priori poleward of the cusp: the magnetic field orientation at Cluster after 0400 is consistent with lobe magnetic field lines in the southern

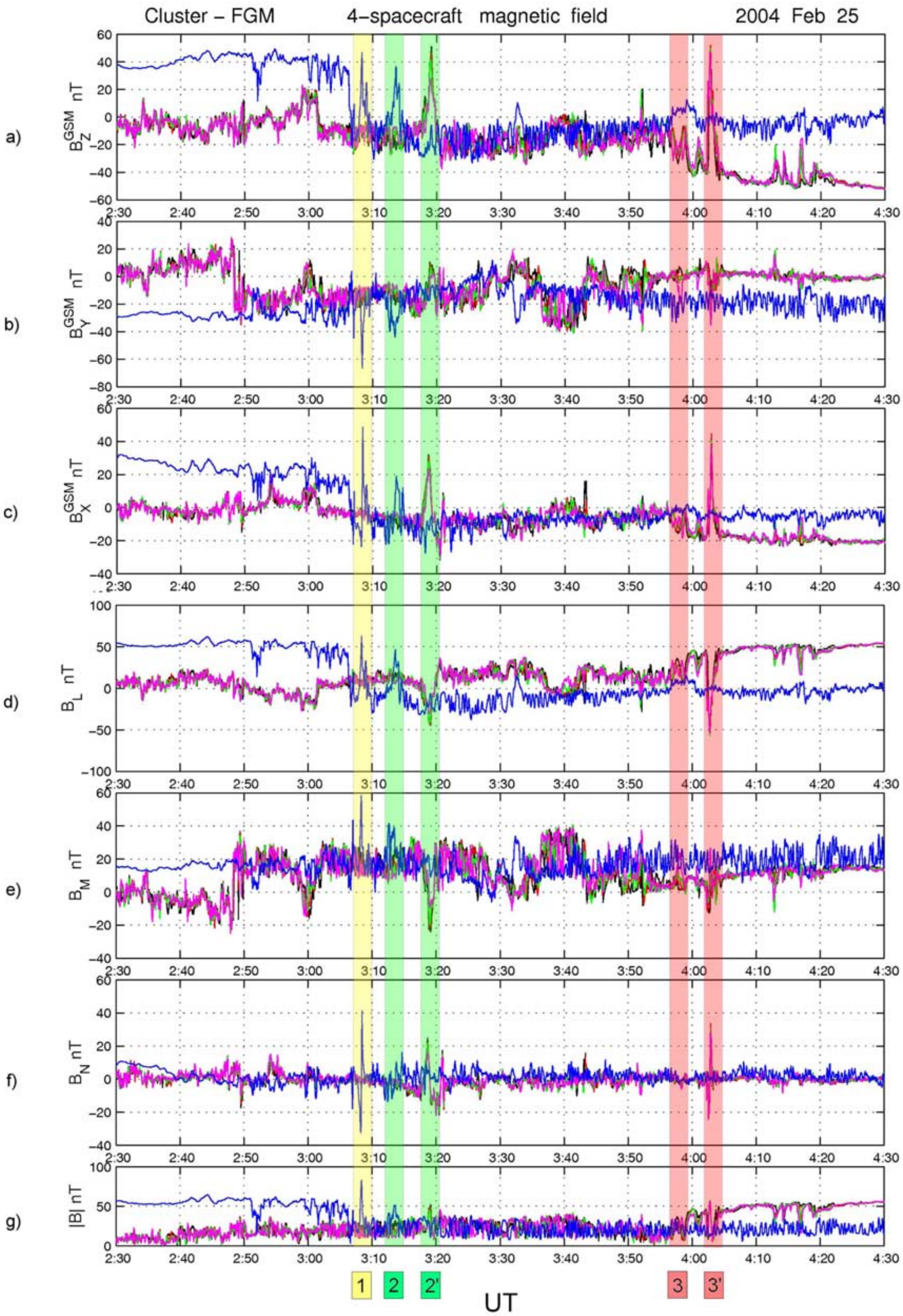

Figure 5. Magnetic field recorded at TC-1 (blue) and Cluster (black, green, magenta, and red). Shown from top to bottom are the Z, Y, X components in GSM, the L, M, N components, and the magnitude of the magnetic field. The events discussed in the paper are marked by vertical color bars and labeled at the bottom of the figure.

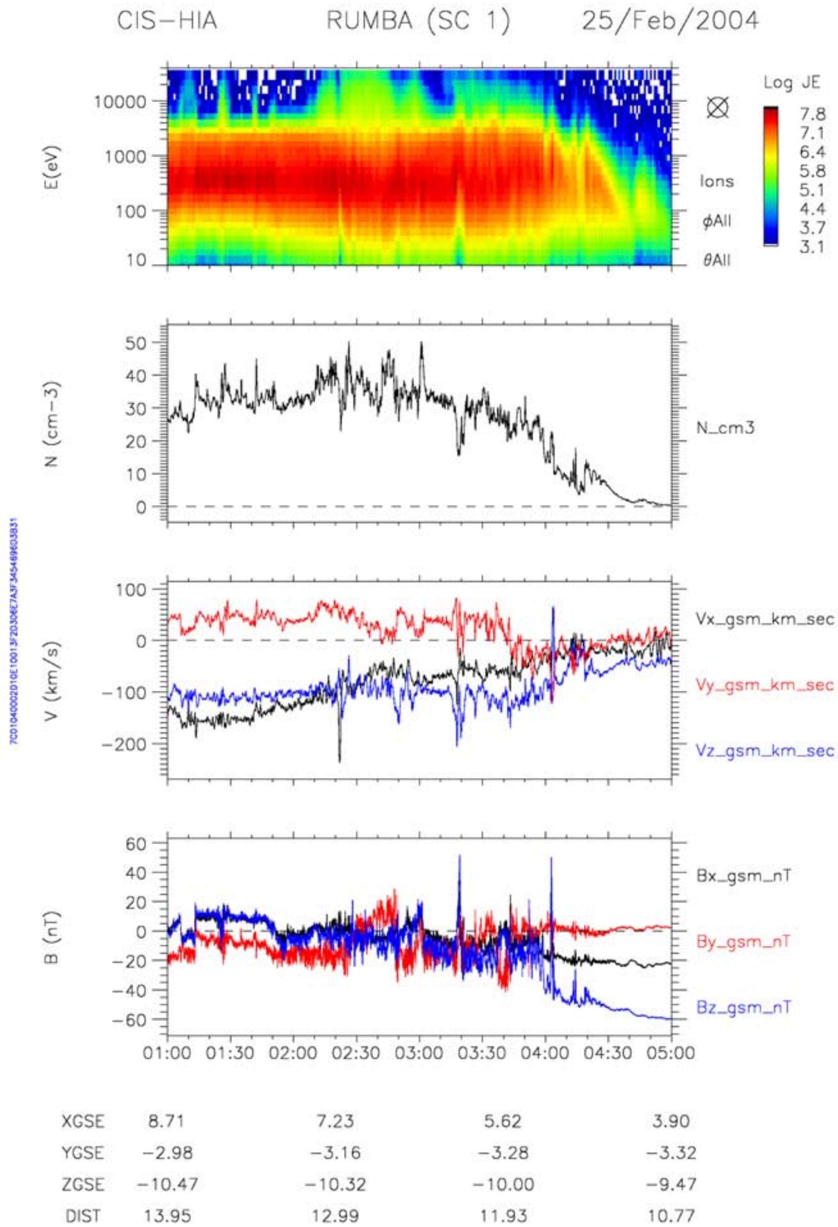

Figure 6. HIA data recorded on board Cluster (SC 1) between 0100 and 0500 UT. Shown from top to bottom are an energy-time spectrogram, the ion number density, the three GSM components of the plasma velocity, and the three GSM components of the magnetic field.

hemisphere: both B_x and B_z are negative (Figures 5c and 5a). It is interesting to notice that from 0210 UT onward, high-energy ions (above 10 keV) are observed and the density increases significantly (from ∼25 up to 35–40 cm^{-3}). Cluster is very likely in a region of field lines connected to the Earth, i.e., just above the magnetospheric cusp but still on the magnetosheath side. The high-energy ions observed are very likely coming up from the magnetosphere on draped open field lines. HIA also observes at least two events, at 0221 and 0318 UT, during which the density drops significantly, the plasma velocity increases, and the ion population loses its low-energy part. Let us focus on the second magnetosheath event (event 2′, second green bar in Figure 5). HIA on board Cluster (Figure 6) observes a substantial decrease in the density (30 down to 15 cm^{-3}) and accelerated magnetosheath plasma (from 120 up to almost 200 km/s in the –Z direction). In the meantime, FGM records a rotation of the magnetic field together with an increase of its amplitude (Figure 5g).

[23] Then, later around 0400 UT, Cluster is about to enter the magnetosphere (low density in CIS data and magnetospheric field in FGM data). At 0403 UT, it observes a large (−, +) FTE (Figure 5f). This FTE is connected to the IMF

turning from southward to northward observed at TC-1 (event 3′).

[24] Let us emphasize that for Cluster, the MVA analysis (Figure 5) was performed on the interval 0403–0420 UT and leads to the following eigenvectors:

N 0.9349 – 0.0814 – 0.3454
M – 0.0844 0.8943 – 0.4394
L 0.3447 0.4400 0.8292

Again, the eigenratio is low (3.5–4) but stable.

3. Interpretation

3.1. Event 1: Evolution of the FTE Observed at TC-1 at 0308 UT

[25] This large FTE, which has an amplitude of +/– 30nT in B_N, has the expected polarity (–, +) for an FTE traveling southward. The reconnection occurs therefore north of TC-1 [*Rijnbeek et al.*, 1982]. Plasma properties within the FTE are recorded by the HIA sensor: depletion of low-energy ions within the FTE, increase of the energy flux of particles whose energy is around 1 keV, and decrease of the ion density from 22 to 10 cm^{-3}. All this suggests an energization of the magnetosheath plasma together with a mixing with magnetospheric plasma (density lower than in the sheath).

[26] We have good reasons to believe that this FTE observed at TC-1 has no counterpart in Cluster data. The structure recorded at Cluster at 0318 UT is very likely something else (this point will be discussed below). This could be at first very intriguing knowing that both spacecraft are quite close in terms of magnetic local time. This has strong implications on the size of the reconnection site, as we will explain later.

3.2. Events 2 and 2′: Nature of the Signature Observed at Both TC-1 and Cluster

[27] At 0314 UT, a structure is observed by FGM on board TC-1. The magnetic field exhibits large amplitude variations: −10 to +30 nT in B_z, +10 to −40 nT in B_y, and −10 to +20 nT in B_x (Figures 5a, 5b, and 5c). Given the locations and the magnetosheath velocity, this structure can be expected to arrive at Cluster about 5 min later. Indeed, at 0318 UT, Cluster-FGM records a large-amplitude magnetic disturbance. Still in Figure 7, which displays a detailed view of event 2’ with the same parameters as in Figure 4, we can see it as positive deflections in all components: B_x (−10 to +30 nT), B_y (−20 to +10 nT), and B_z (−10 to +40 nT).

[28] This could be seen at first glance as an FTE observed at TC-1 first and then at Cluster but there are a few points that need to be detailed:

[29] 1. There is a big difference compared to event 1 for instance. At TC-1, event 2 does not show up as a large bipolar signature in the direction normal to the magnetopause after coordinate transformation (blue curve in Figure 5f) although a small bipolar structure is seen −10 nT to +10 nT in B_N. This structure does not appear to be a clear FTE from that point of view.

[30] 2. Assuming that this is a traveling FTE, a positive deflection first in the component normal to the magnetopause as observed at Cluster (event 2′) is problematic. An FTE traveling southward on the dayside should have a (−, +) polarity, like the one described in the previous section.

[31] 3. If the structure observed is an incursion in the magnetosphere, it would be consistent with data from both satellites: B_z becomes strongly positive as the satellite gets into the magnetosphere on dayside magnetospheric field lines pointing northward and no signature in B_N. At Cluster, the magnetic field observed is also that of the dayside boundary layer (positive B_x and B_z).

[32] Nevertheless, we have performed a Walén test [*Khrabrov and Sonnerup*, 1997] on Cluster data between 0317:48 and 0318:12 UT and it turned out to be successful (lower panel of Figure 8): the linear fit of the V_A versus $V - V_{HT}$ data points has a slope of 0.78 (the slope is ideally 1 for a rotational discontinuity). Cluster did pass through a rotational discontinuity. Although everything suggests that the structure observed at Cluster is the remains of a reconnection event, internal particle and field characteristics are not in favor of ongoing massive particle entry at this stage of the evolution.

[33] Likewise, the electron spectrogram from the PEACE instrument (Figure 9), which displays pitch angle distribution for 20 energy bins, shows bidirectional electrons in the four bins from 29 to 78 eV between 0318 UT and 0319:30 UT and again around 0321 UT. This is typical for newly open field lines [*Owen et al.*, 2001].

[34] Three-dimensional timing analysis performed locally of the leading and trailing edges of the structure leads to two normals oriented as (0.3, 0.8, −0.4) GSM with a velocity of ∼20 km/s and (−0.7, 0.7, −0.3) GSM with a velocity of ∼100 km/s, respectively. That is consistent with a bulge traveling southward. However, the dominating Y component is intriguing. It is difficult to say whether it is physical or due to the elongated Cluster configuration (short separation along *y* axis). Let us not that these velocities and directions of motion are quite different to the deHoffmann-Teller velocity of the structure found: (−120.5; +38.6; −209.4) km/s in GSM. The bulge observed and the plasma in the reconnection layer have different velocities and directions of motion and thus appear not to be related (Figure 10).

3.3. Events 3 and 3′: Inverted FTE in Response to IMF Northward Turning

[35] FTEs are also observed poleward of the cusp for northward IMF [*Fear et al.*, 2005]. As the Cluster satellites were entering the magnetosphere in the southern lobe (Bx < 0 and Bz < 0 after ∼0400 UT in Figure 5), they recorded an FTE at 0403 UT (Figure 5f) with a (−, +) polarity in B_N. This polarity is consistent with an FTE due to reconnection in the lobe under northward IMF and traveling sunward. The Walén test performed on this structure between 0402:50 UT and 0403:22 UT (Figure 11) is positive so we again deal with a rotational discontinuity. The deHoffman-Teller velocity is (25.8; −136.8; −36.9) km/s in GSM and confirms that the structure moves sunward, with a strong Y component. This negative Y component of the velocity reflects the effect of the negative B_y of the IMF: the newly open field lines are pulled dawnward. It is interesting to compare these values to those coming from 3-D timing. As in section 3.2, we have used the four spacecraft to determine the orienta-

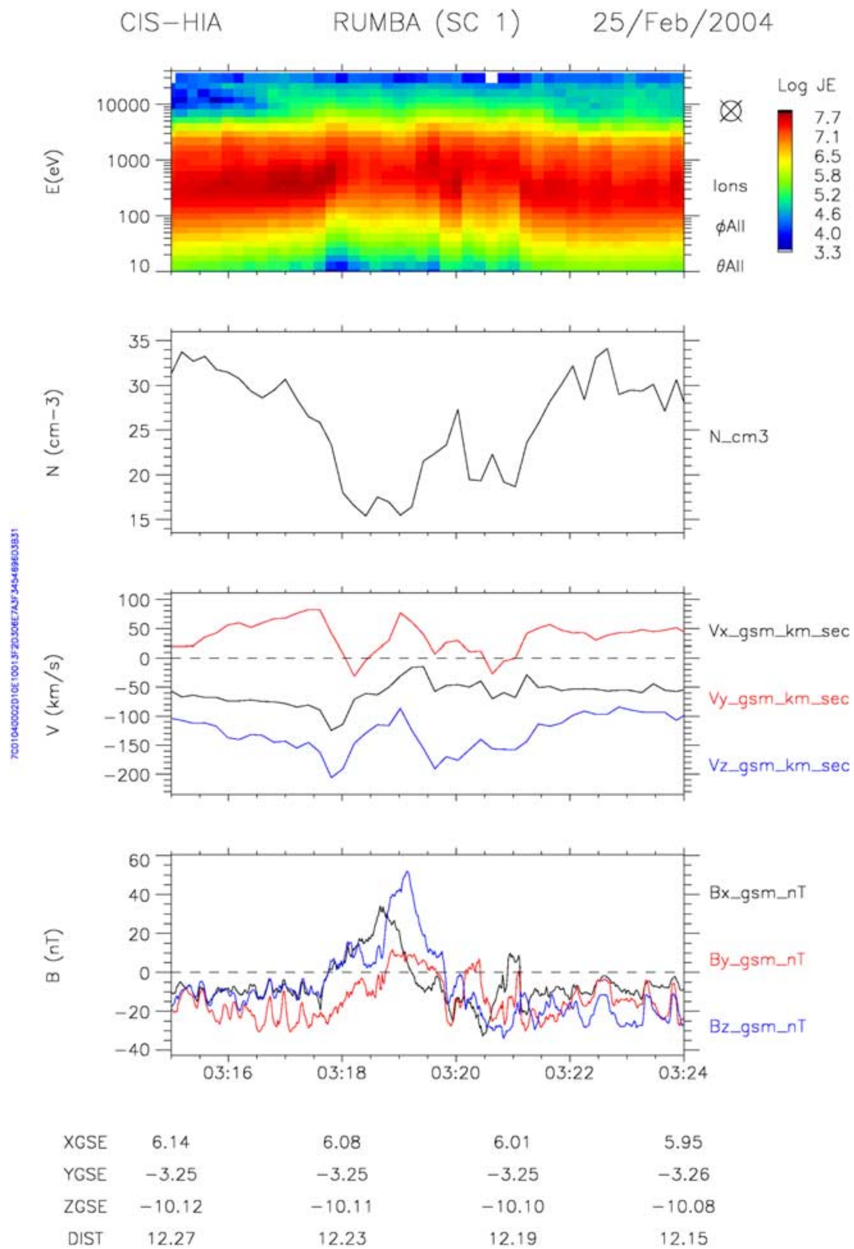

Figure 7. Detailed Cluster CIS-HIA and FGM data on event 2′. Shown from top to bottom are an energy-time spectrogram, the ion number density, the three GSM components of the plasma velocity, and the three GSM components of the magnetic field.

tion and velocity of the motion of this FTE. We have performed the analysis on the center of the FTE. We found that it propagates along the (0.1, −0.9, −0.4) GSM direction with a velocity of 110 km/s.

4. Discussion

[36] We discuss in this section the general properties of the shocked solar wind plasma observed at two distant parts of the magnetosheath as well as the implications that arise from the three events that we have presented in the previous section.

4.1. Magnetosheath Plasma

[37] To discuss the behavior of the magnetosheath plasma as it approaches the magnetosphere and flows along it, we need to compare data from identical instruments onboard Cluster and Double star. Before doing so, let us say a few words on the intercalibration between the instruments. The CIS-HIA data, acquired on board the Cluster spacecraft, have been cross-calibrated with the WHISPER experiment data acquired onboard the same spacecraft. The later provide an absolute value of the plasma density, by identifying the plasma frequency (sounder experiment). On board Double Star TC1, however, there is no sounder experiment,

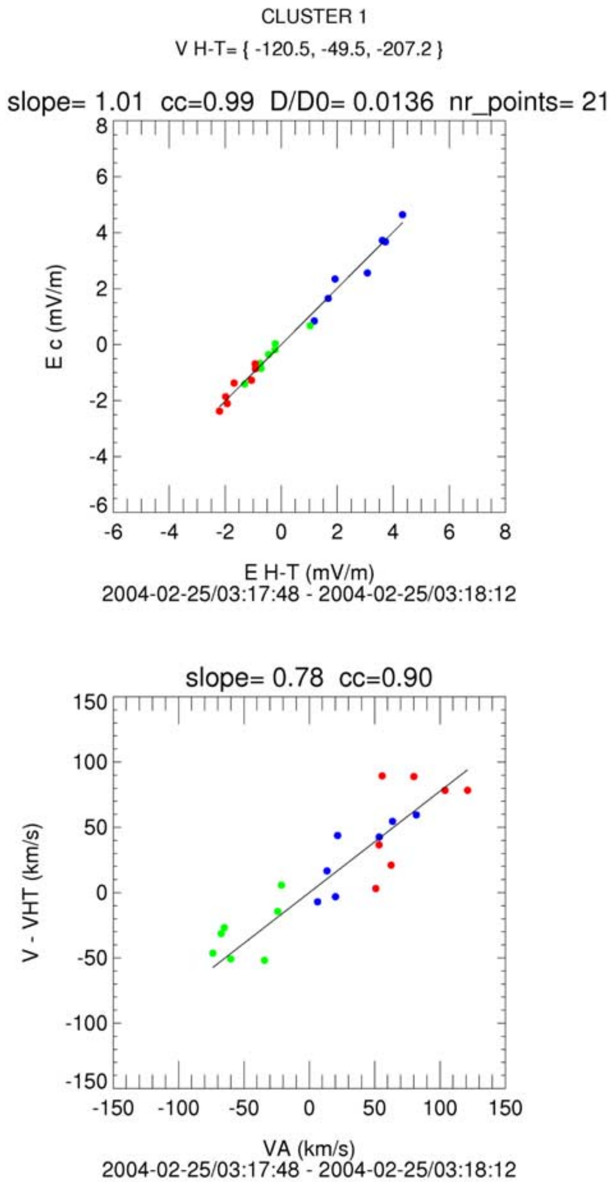

Figure 8. Walén test for the 0318 UT event observed at Cluster.

which makes the identification of the plasma frequency impossible. Moreover, the Cluster and TC1 orbits are quite different, and the separation between them is several Earth radii, which makes a Cluster-TC1 direct intercalibration impossible. For this reason, the HIA data acquired onboard Double Star TC1 have been calibrated using the ''best estimate'' calibration values for absolute sensor efficiency for HIA determined in-flight on board the Cluster spacecraft 1 and spacecraft 2 and have been then corrected for interanode calibrations from the results obtained for this TC1 instrument during ground calibrations in the test chamber.

[38] Comparing our observations in the magnetosheath to the model by *Spreiter et al.* [1966], we find notable differences. The first one is the compression ratio at the bow shock. According to gasdynamic modeling, the compression factor at the bow shock should be ~4 most of the time. Here, we have a solar wind density of about 3–4cm^{-3} and typical values for the magnetosheath density of 25–30 cm^{-3}. This corresponds to a compression ratio around 7. Another significant deviation to the model is that the density in the magnetosheath should decrease as the plasma flow downstream along the magnetopause. Yet, we have reported on a significant increase of the magnetosheath plasma density at Cluster in the vicinity of the cusp compared to Double Star near the subsolar point.

[39] There is no sign of density increase in the solar wind (ACE data, Figure 3) and when TC-1 exits the magnetosphere, it records lower density than Cluster at the same time. Even further from the magnetopause (away from a possible PDL) the density at TC-1 barely reaches 30 cm^{-3} while, at Cluster, it peaks above 40 cm^{-3} (Figure 6). Therefore, the increase in density occurs between TC-1 and Cluster. In fact, this density increase is observed by Cluster quite early, as soon as ~0210 UT. The Cluster spacecraft are then very likely crossing the magnetosheath part of open field lines, which have an end in the Earth's ionosphere. Indeed, from 0210 UT until Cluster crosses the magnetopause at around 0400 UT, oxygen ions are detected by the CODIF sensor [*Rème et al.*, 2001]. Since these O^+ can only come from the magnetosphere, Cluster do observe field lines connected to the Earth. So the higher ion density observed at Cluster may be due, at least partly, to the outflow of magnetospheric ions. Although CODIF measures densities of O^+ of the order of 1.5 cm^{-3} and the same for He^+, these densities are overestimated. It is hard to separate actual measured O^+ ions on the one hand and the spill-over effect (high-energy protons detected as O^+) on the other. Nevertheless, the important point is that high-energy O^+ are detected and those are real. They show that ions are ''leaking'' out of the magnetosphere. Most of those ions are probably protons. They betray the presence of ionospheric/magnetospheric ions in the magnetosheath. Let us recall that the *Spreiter et al.* [1966] model and later improvements [*Spreiter and Stahara*, 1980] do not take into account magnetic reconnection, or any other kind of plasma field interactions in fact.

[40] Another feature of the magnetosheath at Cluster concerns the magnetic field: it appears far more turbulent than at TC-1 near the nose of the magnetopause. It is so turbulent that at Cluster its clock angle, which is supposed to be conserved through the bow shock, no longer matches that of the IMF. As a consequence, a unique time lag to be applied on ACE data so the latter match FGM data on board Cluster is simply impossible to find.

[41] At last, we have noticed some intervals where the parallel ion temperature was of the same order of or even greater than the perpendicular temperature. This is common in the magnetosphere but not in the magnetosheath unless:

[42] 1. Some magnetospheric plasma manages to flow out of the magnetosphere as suggested previously.

[43] 2. The magnetosheath plasma is accelerated and heated along the field lines. Precisely, in a recent paper, *Retinò et al.* [2007] suggested that magnetic reconnection could occur in the turbulent magnetosheath. We already mentioned that the magnetic field recorded at Cluster was highly turbulent in the sheath and thus, conditions for having magnetic reconnection might be fulfilled.

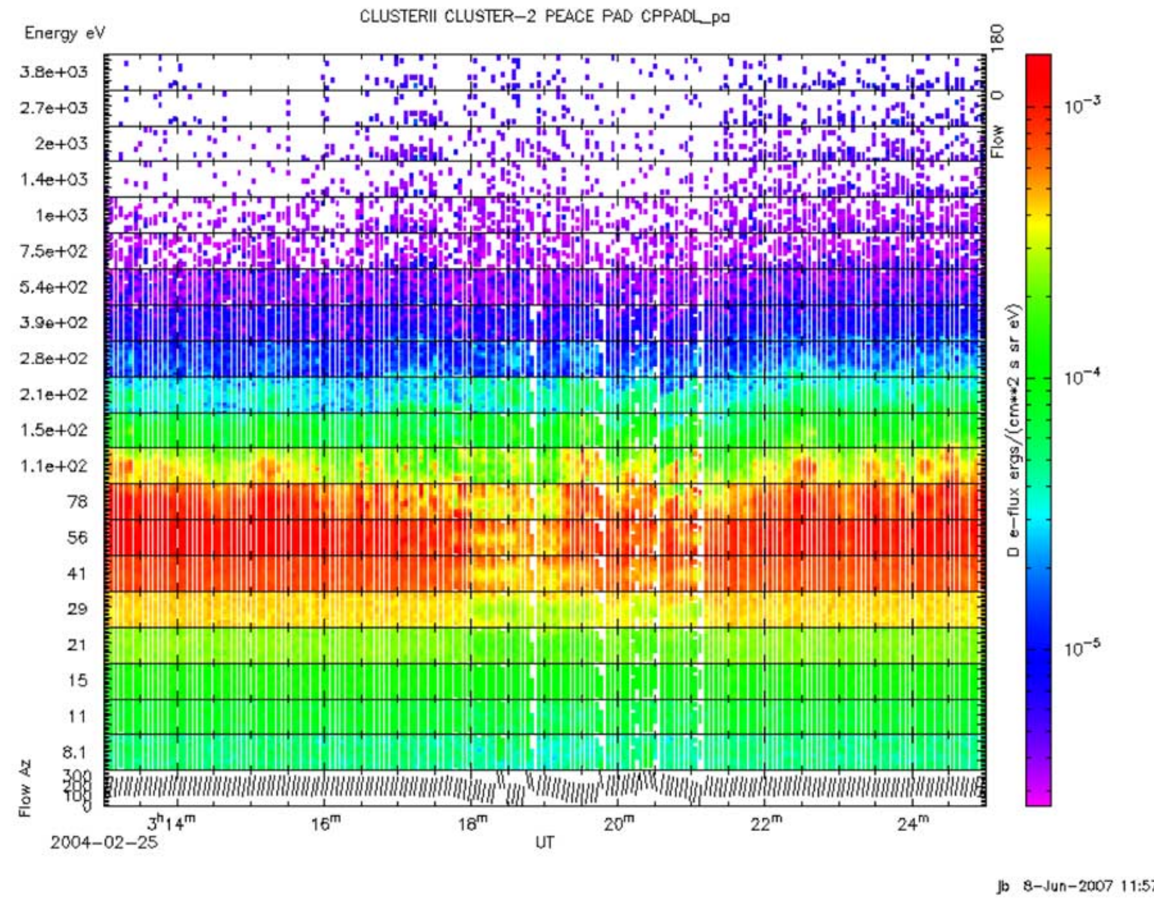

Figure 9. PEACE electron spectrogram corresponding to the 0318 UT event.

4.2. Event 1: Signatures of Reconnection, FTEs Versus Plasma Jets, Reconnection Regime

[44] TC-1 observes both reconnection jets and a clear FTE at 0308:30 UT. These phenomena are thought to be signature of magnetic reconnection. We can then wonder why there are not always observed simultaneously. Plasma jets are observed when a satellite crosses the reconnection layer [*Paschmann et al.*, 1979] where the plasma is strongly accelerated. FTEs on the other hand are a magnetic signature of deviated magnetic field lines and may be observed away from the reconnection layer. Back to our case, the FTE at 0308:30 UT is in fact not quite associated to the plasma jet: the maximum velocity of the jet does not correspond to the maximum of the magnetic field. This may be explained as follows: TC-1 repeatedly encounters the magnetopause (and thus the reconnection layer) due to in/out motion of the magnetosphere and on top of that, an FTE happens to go by. This explanation would imply that FTEs and reconnection jets are not necessarily correlated because their detection is not conditioned by the same constraints. A passing FTE will be detected as soon as a spacecraft is close enough to the magnetopause; plasma jets will be seen as many times as the magnetopause (or rather the reconnection layer) moves back and forth over the spacecraft. The later statement implies that we are observing continuous reconnection on top of which an FTE is observed. This indicates that continuous and pulsed reconnections are not incompatible. We very likely observe continuous reconnection with a varying reconnection rate [*Le et al.*, 2004].

4.3. Motion of Open Flux Tubes, Location and Size of the X Line, and Reconnection Hypotheses

[45] There has been for years a debate on the favorable conditions for magnetic reconnection to occur between the interplanetary and terrestrial magnetic fields. The two hypotheses, antiparallel [*Crooker*, 1979] and component reconnection [*Gonzalez and Mozer*, 1974; *Sonnerup*, 1974], differ in the way the magnetic field lines merge and under which conditions. One of the differences is the size of the reconnection site or line, much longer with component reconnection [*Moore et al.*, 2002].

[46] In our cases, we are able to determine which of the two hypotheses applies to our events. To do so, we have used the model of open flux motion developed by *Cooling et al.* [2001], based of the work by *Cowley and Owen* [1989]. We have run the Cooling model for two locations of the X line. The results of those runs are shown in Figure 12. Figure 12 (top and bottom) displays a Sun view of the Earth's magnetopause with the two cusps materialized by two diamonds. TC-1 and Cluster are respectively represented by a blue and a red star. The first test (Figure 12, top) with an X line centered on (10.2, 2.5, 0.0) in GSM is not satisfactory at all in explaining our observations: open field lines miss both spacecraft. By moving slightly the X line to the south, we have a more favorable configuration (Figure 12,

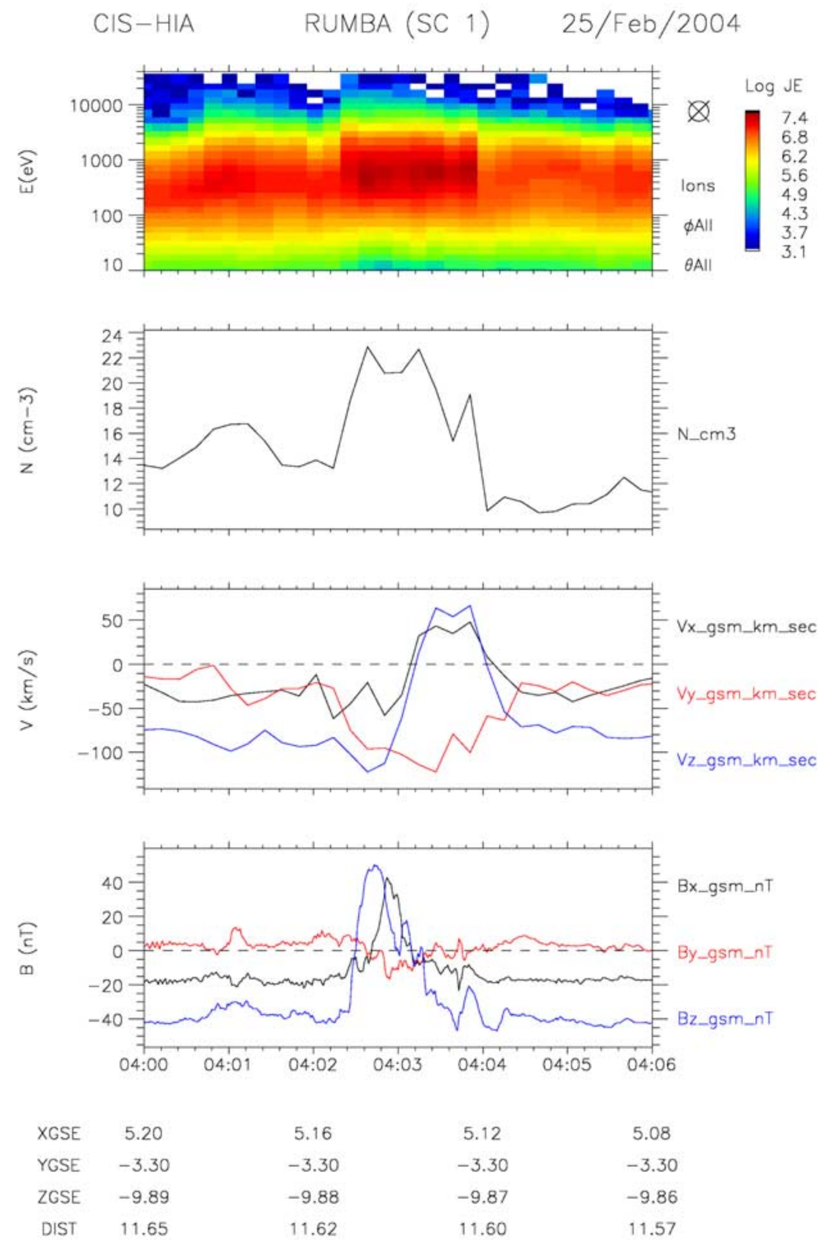

Figure 10. Detailed Cluster CIS-HIA and FGM data on event 3′. Shown from top to bottom are an energy-time spectrogram, the ion number density, the three GSM components of the plasma velocity, and the three GSM components of the magnetic field.

bottom). Knowing the orientation of the IMF, clock angle $\sim 135^\circ$ with negative Y component, the Cooling model predicts that open flux tubes will evolve as shown in Figure 12 (solid and dashed lines for the northern and southern parts, respectively) that is the southern part of newly open flux tubes should progress southward and dawnward.

[47] There is obviously a problem here. With a negative Y component of the IMF and knowing the location of TC-1, we expect all newly open field lines to move in the −Y and −Z direction as show in Figure 12b (in fact we do not really need a model to foresee this). Yet, we observe duskward flows ($V_y \sim +100$ km/s in Figure 4) within the jets. Before going any further in our discussion, we must clarify this disturbing point.

[48] First of all, the velocities that should compare to each other are deHoffman-Teller (dHT) velocities. Indeed, the velocities worked out by the Cooling's model are dHT velocities, which determine the motion of the newly open flux tubes. However, even when we calculate dHT velocities corresponding to the plasma jet observed at TC-1, we obtain typical velocities of he order of (−70, +25, −180) km/s in GSM and again, a lower but still positive Y component of the flow velocity.

[49] We then thought of a problem with the instruments. After having double-checked HIA data on TC-1, we are

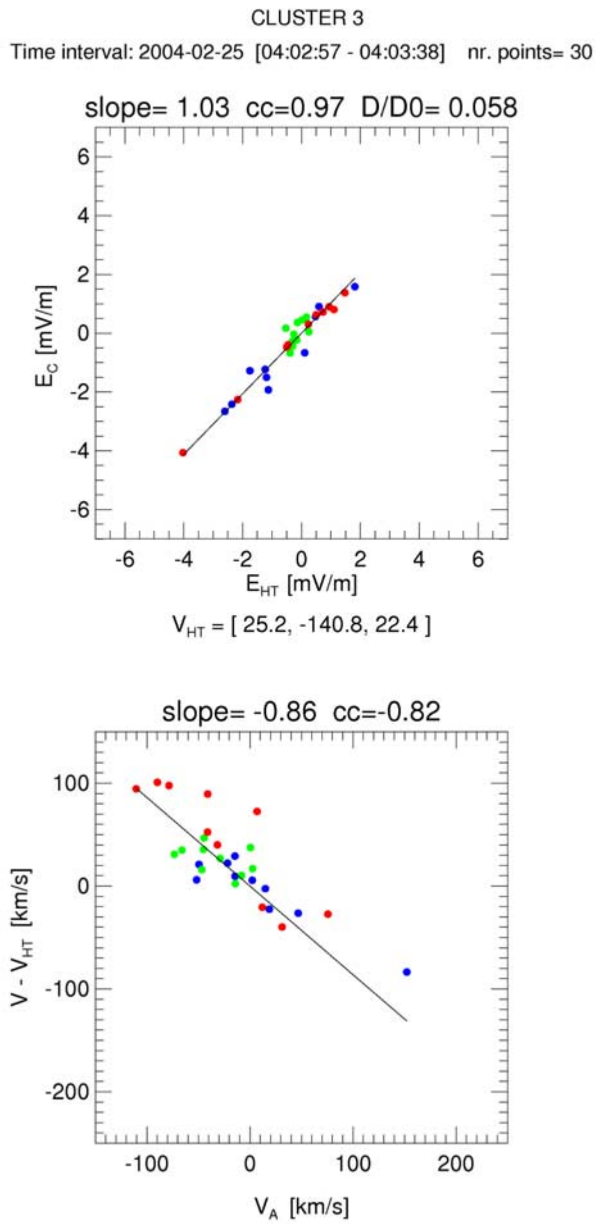

Figure 11. Walén test for the FTE observed at Cluster at 0403 UT.

confident that the measurements are correct. Likewise, the FGM team is confident about the quality of the cleaned FGM data. Besides, the magnetic field orientation measured in the magnetosheath between the jets agrees well with that measured by ACE in the solar wind (negative B_y and B_z). So unless we missed something, we do observe duskward jets at the dayside magnetopause under dawnward and southward IMF.

[50] On the other hand, we do not doubt a second that open field lines attached to the southern polar ionosphere must globally progress dawnward and poleward under dawnward and southward IMF. So the most likely explanation is that TC-1 is very close to the reconnection region, as suspected by the Cooling runs (Figure 12) and that locally, the plasma motion is duskward as observed but eventually becomes dawnward to agree with our current knowledge and with the Cooling model. There is a priori no other way. Let us note that the magnetic field in the boundary layer is oriented dawnward and northward (the angle between the IMF and the geomagnetic field line is small: $\sim 100°$, which is in favor of component reconnection). Freshly reconnected field lines would be first pulled southward and duskward by the magnetic tension and thus be recorded close to the X line with $V_y > 0$. The Cooling model can help us to determine how close. By comparing the two plots in Figure 12, we can estimate the distance between TC-1 and the X line to be 5 R_E at most. Also let us emphasize that when Cluster briefly encounters the reconnection layer at higher latitude (event 2'), the flow is as expected: southward and dawnward. This confirms that, globally, newly open field lines are moving dawnward. This is also confirmed by the fact that neither the jets not the large FTE observed at TC-1 are seen at Cluster.

[51] Indeed, we saw that the 0308 UT FTE (event 1) recorded at TC-1 is not seen by Cluster. Knowing that a sufficiently long X line (it is 8 R_E long in Figure 12) would yield open flux tubes passing at both satellites, it is quite unlikely that reconnected flux tubes from an extended X line would have reached TC-1 but not Cluster.

[52] At last, a X line lying so close to TC-1, i.e., close to the subsolar point, whatever the length of this X line, is also in favor of component reconnection [*Gonzales and Mozer*, 1974; *Sonnerup*, 1974]. The favored reconnection site for antiparallel reconnection would split in two parts, one in each hemisphere, under such IMF conditions [*Crooker*, 1979].

4.4. Nature of Events 2 and 2′

[53] Despite the use of TC-1 and Cluster and of the tests available, it has not been trivial to find out what the nature of event 2 is. It does not clearly show up as a bipolar structure in magnetic field at TC-1 and even though it has a strong positive component in B_N at Cluster, it does not look like a FTE either. Therefore, it seems clear that this event is not a traveling FTE.

[54] On the other hand, we have shown that this structure exhibits signatures of a rotational discontinuity (accelerated plasma, positive Walén test). Both TC-1 and Cluster have therefore encountered newly reconnected field lines.

[55] This event looks at Cluster like a traveling bulge on the magnetopause, whose motion is different to that of the plasma in the reconnection layer. This bulge was assumably created by variations in the magnetosheath flow.

[56] Let us note that nothing in the solar wind parameters could have allowed us to foreseen this behavior (variation created in the foreshock?) but this explanation seems to be the only one that accounts for all our observations: (1) No clear bipolar signature at TC-1 whereas at Cluster, a surface wave has had the time to grow. (2) The amplitude and components of the magnetic field within the incursions are similar to those in the boundary layer (Figure 5). (3) The plasma observed during the incursions corresponds to open field lines. At both TC1 and Cluster, we do observe the reconnection layer and these observations where made possible by an outward motion of the magnetopause at TC1 and a traveling bulge at Cluster.

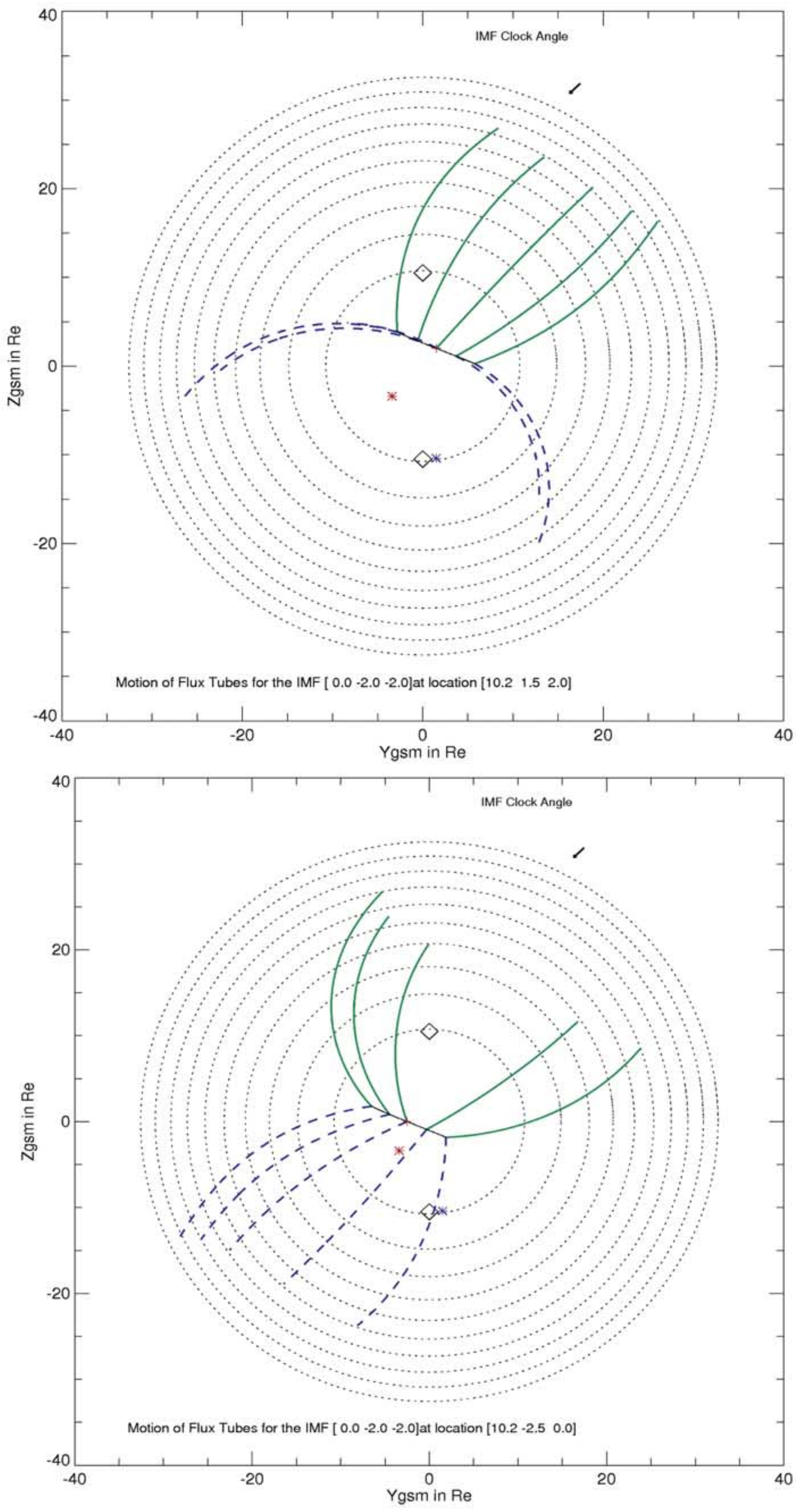
IMF Clock Angle
Motion of Flux Tubes for the IMF [0.0 -2.0 -2.0]at location [10.2 1.5 2.0]
Zgsm in Re
Ygsm in Re
IMF Clock Angle
Motion of Flux Tubes for the IMF [0.0 -2.0 -2.0]at location [10.2 -2.5 0.0]
Zgsm in Re
Ygsm in Re

Figure 12

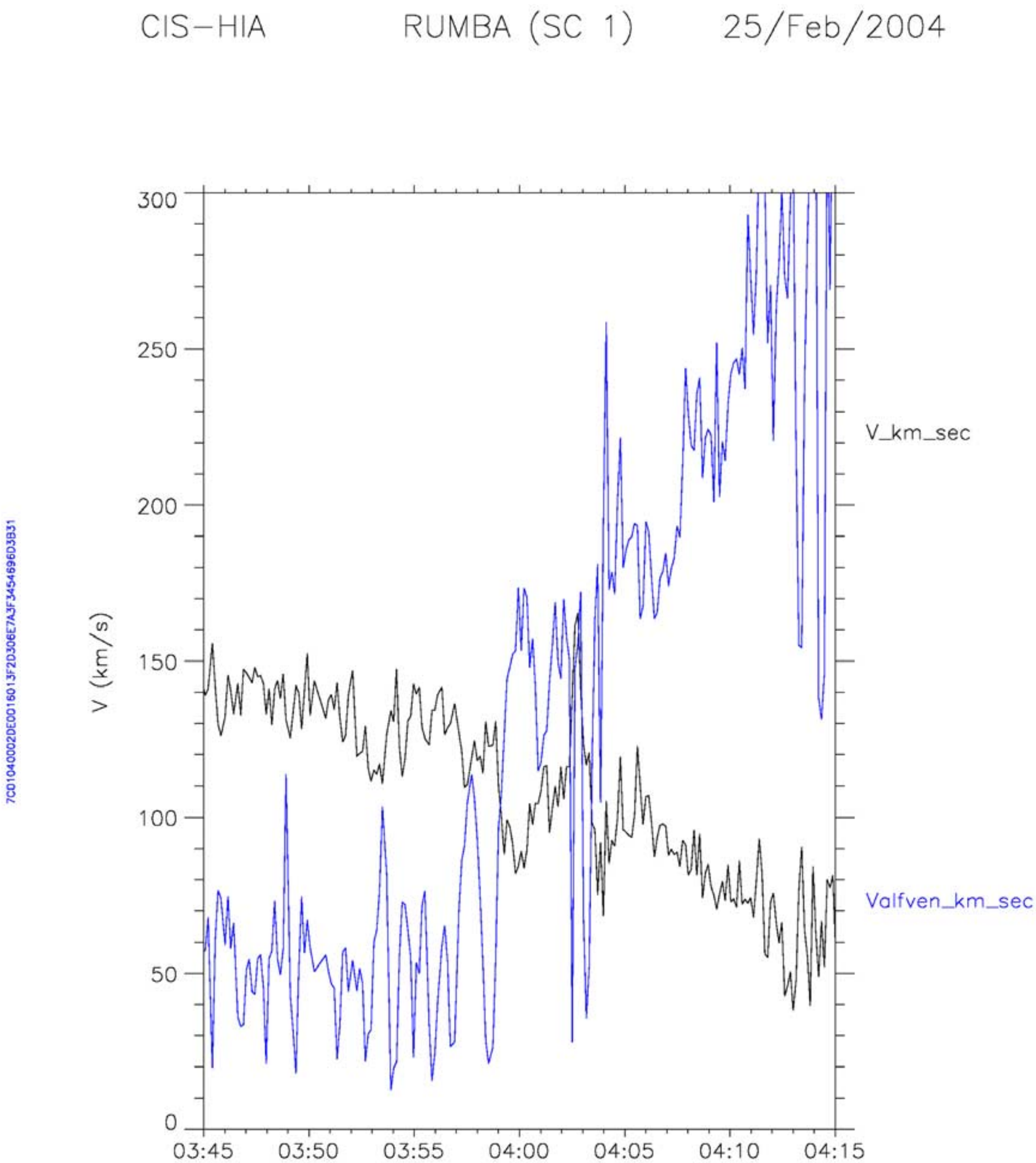

Figure 13. Plasma (black) and Alfvén (blue) velocities measured by Cluster (SC1) in the magnetosheath and magnetosphere around 0404 UT (event 3′).

4.5. Events 3 and 3′: Setup of Reconnection After a Change in IMF Orientation and PDL

[57] Is the response of solar wind-magnetosphere coupling by means of magnetic reconnection to changes in IMF orientation a continuous process, with a reconnection site moving from a place to another? Does magnetic reconnection switch off at some place and to switch on again elsewhere? In either cases, how long does the transition period last?

[58] At midaltitude, fast responses of the cusp, and therefore of the reconnection site, to rapid rotations of the IMF have been reported to occur within minutes [*Pitout et*

Figure 12. Motion of open flux tubes given by the Cooling model for an IMF of (0, −2, −2) nT for an X line centered on the point at the magnetopause whose coordinates in GSM are (10.2, 1.5, 2.0) and (10.2, −2.5, 0.0), respectively, on the top and at the bottom. Green and dashed blues lines represent open field lines pulled toward the north and south, respectively. The two cusps are marked by two diamonds. The red and blue stars locate TC-1 and Cluster, respectively.

al., 2006a; *Escoubet et al.*, 2006]. Curiously enough, on a statistical basis, it was shown that the time for the cusp to fully adjust to new IMF conditions was rather of the order of 20 min [*Pitout et al.*, 2006b].

[59] Here, we have the opportunity to document partly this interesting point by comparing data of Cluster and Double Star to estimate the time reconnection needs to set up. The reverse FTE observed by Cluster at 0403 UT is preceded by a short-lived northward turning of the magnetosheath magnetic field observed by TC1 in the magnetosheath, starting at 0357 UT and ending just after 0400 UT. There is therefore at most 6 min between the detection at TC-1 and the response at Cluster. Knowing that the magnetic field has to convect to the lobe and that the FTE has to travel sunward to reach Cluster, this leaves very little time for reconnection to set up. The time required is in fact more in line with the couple of minutes reported by *Pitout et al.* [2006a].

[60] Finally, we know that to obtain pulsed reconnection poleward of the cusp, a depletion layer needs to form to make the magnetosheath flow sub-Alfvénic. We show in Figure 13 the plasma and Alfvén velocities between 0345 UT and 0415 UT. We see that the magnetosheath flow is super-Alfvénic at these high latitudes (as expected) and that it becomes barely Alfvénic ($V_{sheath} \sim V_{Alfvén}$) near the magnetopause. We therefore do not observe a clear plasma depletion layer (PDL) with $V_{sheath} < V_{Alfvén}$, which explains why the velocity of the FTE is not strongly sunward (~10 km/s).

5. Conclusion

[61] We have reported on an interesting conjunction between Double Star TC-1 and the Cluster fleet, all close to the magnetopause, near the magnetic noon meridian. We know that the combination of the Cluster and Double Star missions is very successful and fruitful for the study of dynamic regions or layers such as the magnetopause.

[62] We have shown that in our case, the magnetosheath density at or slightly poleward of the cusp was of the same order as and at times higher than at lower latitude. We have explained this by magnetic reconnection and leakage of magnetospheric plasma in the sheath.

[63] We have also studied the properties of two FTEs. One was observed at TC-1 near the subsolar point while effects of continuous reconnection were being observed (jets). From the fact that it was not observed at Cluster, we have concluded that the reconnection site from where it originates was relatively limited in size. Also, since the reconnection site is near the subsolar point while the IMF was far from antiparallel to the boundary layer field, we concluded that component reconnection was operating. Another FTE, recorded by Cluster poleward of the cusp, was due to lobe reconnection during a short interval of northward IMF. The short time difference between the moment when the northward turning was detected at TC-1 and when the FTE was observed at Cluster suggests that reconnection process is very fast adjusting to changes in the IMF orientation (a couple of minutes).

[64] At last, the only event recorded at both TC-1 and Cluster was not clearly and undoubtedly identified as an FTE even if both missions records signature of rotational discontinuity. A bulge running along the magnetopause was identified at Cluster. It remains unclear whether this bulge is a traveling FTE or a surface wave. Whatever the answer, this bulge made Cluster sense the reconnection layer very near the southern cusp.

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References

Balogh, A., et al. (2001), The Cluster Magnetic Field Investigation: Overview of in-flight performance and initial results, *Ann. Geophys.*, *19*, 1207–1217.

Bavassano-Cattaneo, M.-B., et al. (2006), Kinetic signatures during a quasi-continuous lobe reconnection event: Cluster Ion Spectrometer (CIS) observations, *J. Geophys. Res.*, *111*, A09212, doi:10.1029/2006JA011623.

Berchem, J., and C. T. Russell (1984), Flux transfer events on the magnetopause: Spatial distribution and controlling factors, *J. Geophys. Res.*, *89*, 6689–6703, doi:10.1029/JA089iA08p06689.

Carr, C., et al. (2005), The Double Star Magnetic Field Investigation: Instrument design, performance and highlights of the first year's observations, *Ann. Geophys.*, *23*, 2713–2732.

Cooling, B. M. A., C. J. Owen, and S. J. Schwartz (2001), Role of magnetosheath flow in determining the motion of open flux tubes, *J. Geophys. Res.*, *106*, 18,763–18,775, doi:10.1029/2000JA000455.

Cowley, S. W. H., and C. J. Owen (1989), A simple illustrative model of open flux tube motion over the dayside magnetopause, *Planet. Space Sci.*, *37*, 1461–1475, doi:10.1016/0032-0633(89)90116-5.

Crooker, N. U. (1979), Dayside merging and cusp geometry, *J. Geophys. Res.*, *84*, 951–959, doi:10.1029/JA084iA03p00951.

Daly, P. W., D. J. Williams, C. T. Russell, and E. Keppler (1981), Particle signature of magnetic flux transfer events at the magnetopause, *J. Geophys. Res.*, *86*, 1628–1632, doi:10.1029/JA086iA03p01628.

Dunlop, M. W., et al. (2005), Combined Cluster/Double Star observations of a close transit across the dayside magnetopause, during a period of quasi-steady reconnection, *Ann. Geophys.*, *23*, 2867–2875.

Escoubet, C. P., M. Fehringer, and M. Goldstein (2001), The Cluster mission, *Ann. Geophys.*, *19*, 1197–1200.

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.

Fairfield, D. H., W. Baumjohann, G. Paschmann, H. Luehr, and D. G. Sibeck (1990), Upstream pressure variations associated with the bow shock and their effects on the magnetosphere, *J. Geophys. Res.*, *95*, 3773–3786, doi:10.1029/JA095iA04p03773.

Farrugia, C. J., H. K. Biernat, N. V. Erkaev, L. M. Kistler, G. Lee, and C. T. Russell (1998), MHD model of the magnetosheath flow: Comparison with AMPE/IRM observations on 24 October 1985, *Ann. Geophys.*, *16*, 518–527, doi:10.1007/s00585-998-0518-7.

Fazakerley, A. N., et al. (2005), The Double Star Plasma Electron and Current Experiment, *Ann. Geophys.*, *23*, 2733–2756.

Fear, R. C., A. N. Fazakerley, C. J. Owen, and E. A. Lucek (2005), A survey of flux transfer events observed by Cluster during strongly northward IMF, *Geophys. Res. Lett.*, *32*, L18105, doi:10.1029/2005GL023811.

Formisano, V., and E. Amata (1976), Solar wind interaction with the Earth's magnetic field: 4. Preshock perturbation of the solar wind, *J. Geophys. Res.*, *81*, 3907–3912, doi:10.1029/JA081i022p03907.

Formisano, V., P. C. Hedgecock, G. Moreno, F. Palmiotto, and J. K. Chao (1973), Solar wind interaction with the Earth's magnetic field: 2. Magnetohydrodynamic bows shock, *J. Geophys. Res.*, *78*, 3731–3744, doi:10.1029/JA078i019p03731.

Gonzalez, W. D., and F. S. Mozer (1974), A quantitative model for the potential resulting from magnetic reconnection with an arbitrary interplanetary magnetic field, *J. Geophys. Res.*, *79*, 4186–4194, doi:10.1029/JA079i028p04186.

Johnstone, A. D., et al. (1997), PEACE: A plasma electron and current experiment, *Space Sci. Rev.*, *79*, 351–398, doi:10.1023/A:1004938001388.

Kawano, H., and C. T. Russell (2005), Dual-satellite observations of the motions of flux transfer events: Statistical analysis with ISEE 1 and ISEE 2, *J. Geophys. Res.*, *110*, A07217, doi:10.1029/2004JA010821.
Khrabrov, A. V., and B. U. Ö Sonnerup (1997), DeHoffman-Teller analysis, in *Analysis Methods for Multi-Spacecraft Data*, *ISSI Sci. Rep. SR-001*, edited by G. Paschmann and P. W. Daly, p. 185, ESA Publ. Div., Noordwijk, Netherlands.
Le, G., et al. (2004), Coordinated polar spacecraft, geosynchronous spacecraft, and ground-based observations of magnetopause processes and their coupling to the ionosphere, *Ann. Geophys.*, *22*, 4329–4350.
Liu, Z. X., C. P. Escoubet, Z. Pu, H. Laakso, J. K. Shi, C. Shen, and M. Hapgood (2005), The Double Star mission, *Ann. Geophys.*, *23*, 2707–2712.
Longmore, M., S. J. Schwartz, J. Geach, B. M. A. Cooling, I. Dandouras, E. A. Lucek, and A. N. Fazakerley (2005), Dawn-dusk asymmetries and sub-Alfvénic flow in the high and low latitude magnetosheath, *Ann. Geophys.*, *23*, 3351–3364.
Louarn, P., A. Fedorov, E. Budnik, G. Fruit, J. A. Sauvaud, C. C. Harvey, I. Dandouras, H. Rème, M. C. Dunlop, and A. Balogh (2004), Cluster observations of complex 3D magnetic structures at the magnetopause, *Geophys. Res. Lett.*, *31*, L19805, doi:10.1029/2004GL020625.
Marchaudon, A., J.-C. Cerisier, J.-M. Bosqued, M. W. Dunlop, J. A. Wild, P. M. E. Décréau, M. Förster, D. Fontaine, and H. Laakso (2004), Transient plasma injections in the dayside magnetosphere: One-to-one correlated observations by Cluster and SuperDARN, *Ann. Geophys.*, *22*, 141–158.
Marchaudon, A., et al. (2005), Simultaneous Double Star and Cluster FTEs observations on the dawnside flank of the magnetosphere, *Ann. Geophys.*, *23*, 2877–2887.
Moore, T. E., M.-C. Fok, and M. O. Chandler (2002), The dayside reconnection X line, *J. Geophys. Res.*, *107*(A10), 1332, doi:10.1029/2002JA009381.
Němeček, Z., J. Šafráncová, G. N. Zastenker, P. Pisolf, K. I. Paularena, and J. D. Richardson (2000), Observations of the radial magnetosheath profile and comparison with gasdynamic model predictions, *Geophys. Res. Lett.*, *27*(17), 2801–2804, doi:10.1029/2000GL000063.
Owen, C. J., et al. (2001), Cluster PEACE observations of electrons during magnetospheric flux transfer events, *Ann. Geophys.*, *19*, 1509–1522.
Paschmann, G., I. Papamastorakis, N. Sckopke, G. Haerendel, B. U. Ö. Sonnerup, S. J. Bame, J. R. Asbridge, J. T. Gosling, C. T. Russel, and R. C. Elphic (1979), Plasma acceleration at the Earth's magnetopause - Evidence for reconnection, *Nature*, *282*, 243–246, doi:10.1038/282243a0.
Paschmann, G., G. Haerendel, I. Papamastorakis, N. Sckopke, S. J. Bame, J. T. Gosling, and C. T. Russell (1982), Plasma and magnetic field characteristics of magnetic flux transfer events, *J. Geophys. Res.*, *87*, 2159–2168, doi:10.1029/JA087iA04p02159.
Pitout, F., C. P. Escoubet, B. Klecker, and H. Rème (2006a), Cluster survey of the middle altitude cusp: 1. Size, location, and dynamics, *Ann. Geophys.*, *24*, 3011–3026.
Pitout, F., C. P. Escoubet, Y. Bogdanova, E. Georgescu, A. Fazakerley, and H. Rème (2006b), Response of the mid-altitude cusp to rapid rotations of the IMF, *Geophys. Res. Lett.*, *33*, L11107, doi:10.1029/2005GL025460.
Rème, H., et al. (2001), First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment, *Ann. Geophys.*, *19*, 1303–1354.
Rème, H., et al. (2005), The HIA instrument onboard the Tan Ce 1 Double Star near-Equatorial Spacecraft and its first results, *Ann. Geophys.*, *23*, 2757–2774.
Retinò, A., et al. (2005), Cluster multispacraft observations at the high-latitude duskside magnetopause: Implications for continuous and component magnetic reconnection, *Ann. Geophys.*, *23*, 461–473.
Retinò, A., D. Sundkvist, A. Vaivads, F. Mozer, M. André, and C. J. Owen (2007), In situ evidence of magnetic reconnection in turbulent plasma, *Nature Phys.*, *3*, 236–238, doi:10.1038/nphys574.
Rijnbeek, R. P., S. W. H. Cowley, D. J. Southwood, and C. T. Russell (1982), Observations of reverse polarity flux transfer events at the Earth's dayside magnetopause, *Nature*, *300*, 23–26, doi:10.1038/300023a0.
Rijnbeek, R. P., S. W. H. Cowley, D. J. Southwood, and C. T. Russell (1984), A survey of dayside flux transfer events observed by ISEE 1 and 2 magnetometers, *J. Geophys. Res.*, *89*, 786–800, doi:10.1029/JA089iA02p00786.
Russell, C. T., and R. C. Elphic (1978), Initial ISEE magnetometer results: Magnetopause observations, *Space Sci. Rev.*, *22*, 681–715, doi:10.1007/BF00212619.
Russell, C. T., and R. C. Elphic (1979), ISEE observations of flux transfer events at the dayside magnetopause, *Geophys. Res. Lett.*, *6*, 33–36, doi:10.1029/GL006i001p00033.
Šafráncová, J., M. Hayosh, Z. Němeček, and L. Prech (2004), Magnetosheath investigations: Interball contributions to the topic, in *Multiscale Processes in the Earth's Magnetosphere: From Interball to Cluster*, edited by J. A. Sauvaud and Z. Nemecek, pp. 73–94, Kluwer Acad., Dordrecht, Netherlands.
Sibeck, D. G. (1990), A model for the transient magnetospheric response to sudden solar wind dynamic pressure variations, *J. Geophys. Res.*, *95*, 3755–3771, doi:10.1029/JA095iA04p03755.
Sonnerup, B. U. Ö. (1974), The magnetopause reconnection rate, *J. Geophys. Res.*, *79*, 1546–1549, doi:10.1029/JA079i010p01546.
Sonnerup, B. U. Ö., and L. J. Cahill Jr. (1967), Magnetopause structure and attitude from Explorer 12 observations, *J. Geophys. Res.*, *72*, 171–183, doi:10.1029/JZ072i001p00171.
Sonnerup, B. U. Ö., and M. Scheible (1997), Minimum and maximum variance analysis, *Analysis Methods for Multi-Spacecraft Data*, *ISSI Sci. Rep. SR-001*, edited by G. Paschmann and P. W. Daly, p. 185, ESA Publ. Div., Noordwijk, Netherlands.
Southwood, D. J., C. J. Farrugia, and M. A. Sounders (1988), What are flux transfer events, *Planet. Space Sci.*, *36*, 503–508, doi:10.1016/0032-0633(88)90109-2.
Spreiter, J. R., and A. Y. Alksne (1968), Comparison of theoretical predictions of the flow and magnetic fields exterior to the magnetosphere with the observations of Pioneer 6, *Planet. Space Sci.*, *16*, 971–979, doi:10.1016/0032-0633(68)90013-5.
Spreiter, J. R., and S. S. Stahara (1980), A new predictive model for determining solar wind-terrestrial planet interactions, *J. Geophys. Res.*, *85*, 6769–6777, doi:10.1029/JA085iA12p06769.
Spreiter, J. R., A. L. Summers, and A. Y. Alksne (1966), Hydrodynamic flow around the magnetosphere, *Planet. Space Sci.*, *14*, 223–250, doi:10.1016/0032-0633(66)90124-3.
Thomsen, M. F., J. A. Stansberry, S. J. Bame, S. A. Fuselier, and J. T. Gosling (1987), Ion and electron velocity distributions within flux transfer events, *J. Geophys. Res.*, *92*, 12,127–12,136, doi:10.1029/JA092iA11p12127.
Wang, Y. L., et al. (2005), Initial results of high-latitude magnetopause and low-latitude flank flux transfer events from 3 years of Cluster observations, *J. Geophys. Res.*, *110*, A11221, doi:10.1029/2005JA011150.
Wang, Y. L., R. C. Elphic, B. Lavraud, M. G. G. T. Taylor, J. Birn, C. T. Russell, J. Raeder, H. Kawano, and X. X. Zhang (2006), Dependence of flux transfer events on solar wind conditions from 3 years of Cluster observations, *J. Geophys. Res.*, *111*, A04224, doi:10.1029/2005JA011342.
Zwan, B. J., and R. A. Wolf (1976), Depletion of solar wind plasma near a planetary boundary, *J. Geophys. Res.*, *81*, 1636–1648, doi:10.1029/JA081i010p01636.

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