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Evidence for magnetic reconnection initiated in the magnetosheath

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[1] We report Cluster spacecraft 1 observations of a reconnection exhaust embedded in the magnetosheath flow. The reconnection evidence consists of (1) accelerated plasma outflows, (2) interpenetrating ion beams, (3) reconnection inflows and (4) the associated tangential reconnection electric field. Furthermore, Hall magnetic fields were observed with no gaps in the middle of the exhaust. Together with the exhaust thickness being $\sim$ 10 ion skin depths, this implies that the spacecraft crossed through the ion diffusion region. The dimensionless reconnection rate determined independently using the plasma and electric field measurements was $\sim$0.07, implying fast reconnection. The same (but 36 times thicker) current sheet was observed upstream in the solar wind by the ACE and Wind spacecraft but without the reconnection signatures. These observations suggest that reconnection was initiated in the magnetosheath due to compression of the (non-reconnecting) solar wind current sheet at the bow shock and against the dayside magnetopause. **Citation:** Phan, T. D., G. Paschmann, C. Twitty, F. S. Mozer, J. T. Gosling, J. P. Eastwood, M. Øieroset, H. Rème, and E. A. Lucek (2007), Evidence for magnetic reconnection initiated in the magnetosheath, *Geophys. Res. Lett.*, *34*, L14104, doi:10.1029/2007GL030343.

1. Introduction

[2] Magnetic reconnection in a current sheet converts magnetic energy into particle energy. The reconnection process starts in the minuscule diffusion region but its consequences are large scale. Until recently, all of the in-situ observations of reconnection in space were made in the Earth's magnetosphere by observing outflowing plasma jets [e.g., *Paschmann et al.*, 1979] as well as microphysical processes inside the diffusion region [e.g., *Øieroset et al.*, 2001; *Mozer et al.*, 2002]. Despite decades of observations, fundamental questions concerning the onset and evolution of reconnection remain.

[3] The recent discovery of reconnection exhausts in the solar wind demonstrates that the solar wind is an ideal laboratory for reconnection studies [*Gosling et al.*, 2005]. Because of the presence of large-scale current sheets with relatively stable boundary conditions in the solar wind, conditions that are rare in the Earth's magnetosphere, solar wind current sheets offer unprecedented opportunities to investigate the large-scale properties of reconnection. For example, it has been reported that the reconnection X-line in solar wind reconnection events can extend at least hundreds of Earth radii (tens of thousands ion inertial lengths) and reconnection can remain continuous for many hours (or thousands of ion gyroperiods) [*Phan et al.*, 2006; *Gosling et al.*, 2007]. X-lines of such extent could not have been observed in the magnetosphere.

[4] Here we report in-situ detection of a reconnection exhaust initiated in yet another region in space, namely the magnetosheath downstream of the Earth's bow shock. Because the observations of reconnection in the magnetosheath may occur soon after its initiation, this region is uniquely suited for the investigations of the onset and evolution of reconnection.

2. Spacecraft Locations and Instrumentations

[5] In this paper we discuss observations from Cluster-1, which detected the passage of a current sheet on 2003-01-14 at $\sim$06:12 UT, while in the dusk magnetosheath, below the equatorial plane, at GSE [6.7, 2.0, $-$9.5] R_E. The magnetopause was encountered about an hour later (at 07:06 UT). The radial distance between the magnetosheath current sheet and the magnetopause crossing was $\sim$0.8 R_E. The same current sheet was observed upstream in the solar wind by ACE (at GSE [237.5, $-$27.4, 23.2] R_E), and by Wind (at GSE [183.9, $-$85.4, $-$8.8] R_E). Note that while ACE was close to L1, Wind was 85 R_E dawnward of the Sun-Earth line.

[6] This study uses 4s resolution data from the Cluster ion composition (CIS/CODIF) and electric field (EFW) experiments, together with high-resolution (22 samples/s) magnetic field (FGM) data. The GSE-z component of the electric field was constructed from the x and y components based on the assumption that $E_{//} = 0$. Solar wind ion moments were obtained from Wind/3DP (at 3s resolution) and from ACE/SWEPAM (at 64s resolution). Solar wind magnetic fields are from the Wind/MFI (at 3s resolution) and ACE/MAG (at 0.35s resolution) experiments.

[7] The basic elements of the event and the current sheet in (LMN) coordinates are summarized in Figure 1.

3. Cluster-1 Observations of Reconnection in the Magnetosheath

3.1. Overview

[8] The Cluster-1 data for this event are shown in Figure 2 in LMN and in Figure 3 in GSE coordinates. Cluster-1 detected the passage of a current sheet at $\sim$06:12 UT in the magnetosheath (Figures 2a and 3b) with embedded accelerated ion flow (Figures 2c and 3c). The magnetic shear across the entire field reversal was $\sim$162°. The 7 nT guide

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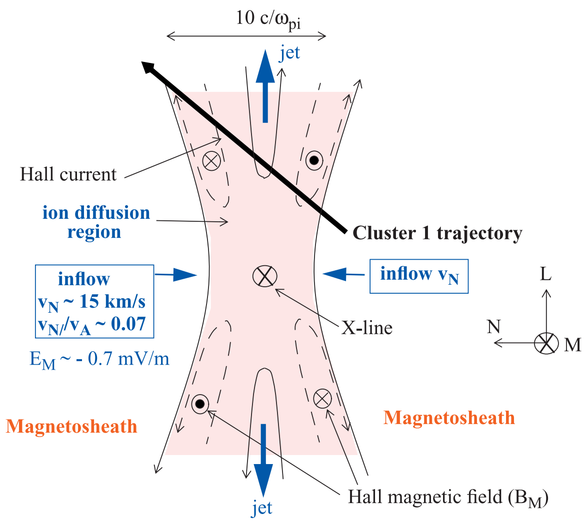

Figure 1. Schematic of the Cluster-1 crossing of a reconnection layer in a magnetosheath current sheet surrounding the diffusion region. The LMN current sheet coordinate system is defined with N along the overall current sheet normal, M along the guide field (X-line) direction and L along the anti-parallel magnetic field direction. The coordinate system is obtained from the minimum variance analysis [*Sonnerup and Cahill*, 1967] based on the magnetic field measured by Cluster 1 in the 06:11:35–06:12:35 UT interval on January 14, 2003. The current sheet normal, ($0.93\hat{\mathbf{x}}$, $0.06\hat{\mathbf{y}}$, $-0.36\hat{\mathbf{z}}$) in GSE, is nearly sunward directed. The X-line (the intermediate variance direction) is oriented along ($0.21\hat{\mathbf{x}}$, $-0.89\hat{\mathbf{y}}$, $0.41\ \hat{\mathbf{z}}$) in GSE. Cluster-1 observed the reconnection plasma inflow and outflow, as well as the bi-polar Hall magnetic field. The sketch is for idealized symmetric boundary conditions whereas the present event shows slight density asymmetry as well as the presence of tangential shear flows. The oblique trajectory of Cluster 1 is due to the southward and anti-sunward motion of the magnetosheath current sheet past the spacecraft.

field (B_M just outside the current sheet in Figure 2b) was 15% of the 48 nT anti-parallel field (Figure 2a). The abrupt changes in the anti-parallel field B_L at the two edges and a plateau in between indicate that the current sheet was bifurcated. The southward ($v_{z,GSE} < 0$) and duskward ($v_{y,GSE} > 0$) ambient magnetosheath flow (Figure 3c) was consistent with the spacecraft location being below the ecliptic plane and duskward of the subsolar point. The ion flow enhancements in the current sheet (relative to the ambient magnetosheath flow) were in the GSE +x, +y, and +z direction; remarkably, the ion flow in the current sheet reversed direction and pointed northward ($v_z > 0$). The velocity components were anti-correlated (correlated) with the components of the magnetic field at the leading (trailing) edge of the bifurcated current sheet. These properties of the plasma and field are qualitatively consistent with the spacecraft crossing a reconnection exhaust northward, duskward, and sunward of the X-line (see Figure 1). The observed ion flow change across the edges of the exhaust was 65% of the predicted change according to the rotational discontinuity condition [*Hudson*, 1970] $\Delta\mathbf{v} = \pm(1-\alpha_1)^{1/2}(\mu_0\rho_1)^{-1/2}[\mathbf{B}_2\rho_1/\rho_2 - \mathbf{B}_1]$. The subscripts 1 and 2 denote the inflow and outflow regions, respectively. The negative (positive) sign is chosen for the leading (trailing) edge of the bifurcated current sheet. $\alpha = (p_\parallel - p_\perp)\mu_0/B^2$ is the pressure anisotropy factor, ρ is the ion mass density. The (substantially) sub-Alfvenic ion flow may be due in part to the spacecraft being in the ion diffusion region where the ions are decoupled from the magnetic field (see Section 3.3 below). The density (Figure 3d) and temperature (Figure 3e) were enhanced while the magnetic field strength was reduced in the exhaust, consistent with the Petschek model of reconnection [*Petschek*, 1964] where the exhaust is bounded by Alfven and/or slow mode waves.

[9] In addition to the fluid signatures of reconnection, Cluster-1 also detected the presence of field-aligned counterstreaming ion beams (Figure 4), providing further evidence for magnetic connection across the exhaust [see *Gosling et al.*, 2005].

3.2. Reconnection Rate and Exhaust Width

[10] Figure 2d shows that the flow velocity normal to the exhaust had a shift of ∼30 km/s (from −20 to −50 km/s)

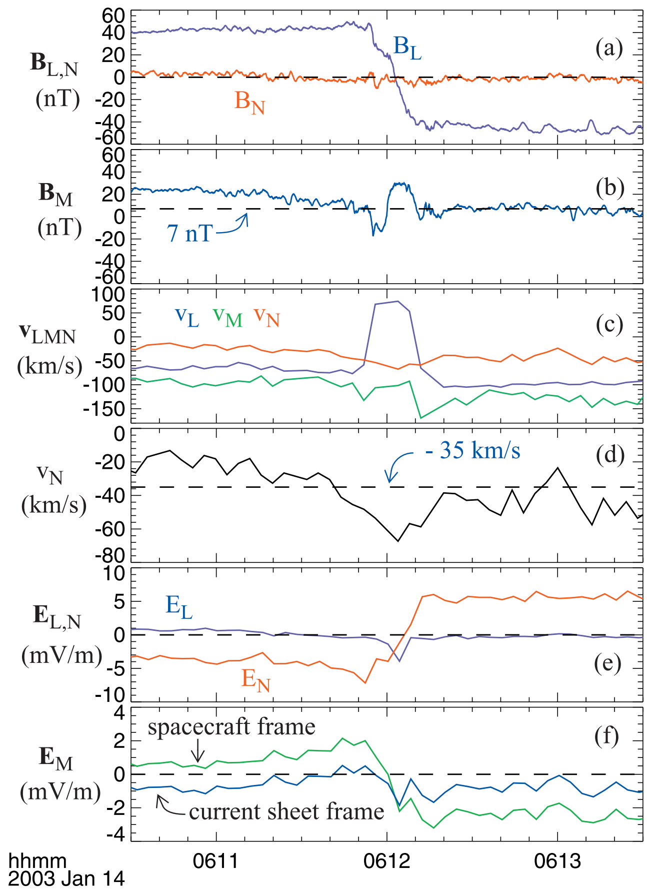

Figure 2. Cluster-1 data around the exhaust in the LMN coordinate system. (a) Anti-parallel, L, and normal, N, components of the magnetic field, (b) 'out-of-plane', M, magnetic field, (c) LMN components of the proton velocity, (d) expanded plot of the proton flow component normal to the current sheet, (e) L and N components of the electric field, and (f) M component of the electric field in the spacecraft frame (green) and in the current sheet frame moving at −35 km/s along the normal (blue).

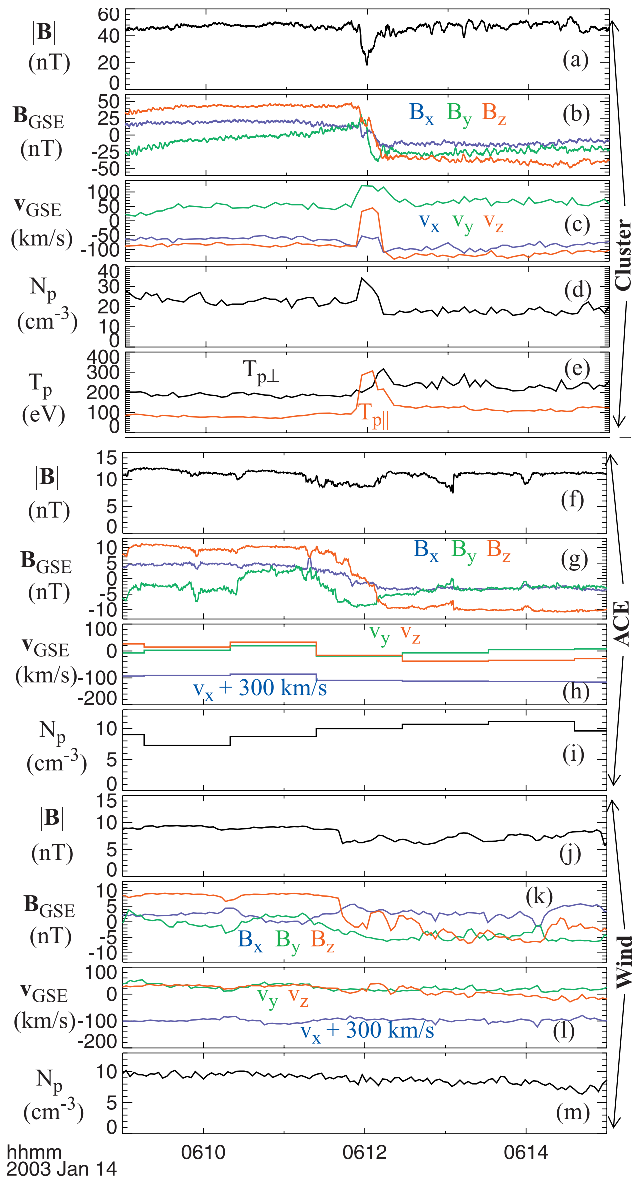

Figure 3. (a–f) Cluster-1 measurements of magnetic field magnitude and components, proton velocity, density, and temperature, respectively, around the crossing of a bifurcated current sheet in the magnetosheath. (f–i) ACE measurements of magnetic field magnitude and components, proton velocity and density around its crossing of the same current sheet. The ACE time series have been shifted in time by 4080s. (j–m) Wind measurements of magnetic field magnitude and components, proton velocity and density around its crossing of the same current sheet. The Wind time series have been shifted in time by 3660s. All measurements are in GSE.

from one side of the exhaust to the other. This shift is consistent with a reconnection inflow of $v_{N,rec}$ = 15 km/s in the frame of the current sheet (which convects with the magnetosheath flow at $v_N \sim -35$ km/s). With a 48 nT antiparallel magnetic field carried into the reconnection region at 15 km/s, the implied reconnection electric field was $E_M \sim -0.72$ mV/m. The dimensionless reconnection rate, $v_{n,rec}/v_A$, was ~0.07, where v_A = 220 km/s was the Alfvén speed in the inflow region on the leading edge side of the exhaust.

[11] The reconnection electric field was also directly measured. Figure 2e shows the electric field in the current sheet frame, obtained by a translation of $v_N = -35$ km/s (corresponding to the current sheet convection speed). This 35 km/s translation also resulted in a roughly constant E_M across the exhaust, which provides further consistency check of the 35 km/s convection speed of the exhaust. The resulting electric field E_M across the exhaust is mostly negative, as expected for reconnection. The average $\langle E_M \rangle \sim -0.67$ mV/m for the 06:10:30–06:13:30 interval is consistent with the reconnection electric field inferred from the plasma inflow velocity and magnetic field. However, this is an approximate value considering the level of fluctuations in E_M.

[12] With an exhaust convection speed of 35 km/s along its normal and the 15s duration of the exhaust crossing, the exhaust width was 525 km or 10 ion skin depths.

3.3. Hall Magnetic Field

[13] Figure 2b shows the presence of bipolar excursions of B_M in the exhaust with an amplitude of ~22 nT, superimposed on a guide field of ~7 nT (horizontal dashed line in Figure 2b). The nearly sinusoidal negative-then-positive B_M in the exhaust is consistent with this being the Hall magnetic field for an exhaust crossing north of the X-line (see Figure 1). The ~46% Hall field (relative to the antiparallel field of 48 nT) is similar in size to previous reports of Hall fields in the magnetosphere [e.g., *Øieroset et al.*, 2001; *Mozer et al.*, 2002].

[14] An intriguing feature of the Hall field is that the B_M profile was steepest, i.e., no plateau (or gap), in the middle of the exhaust, even though the spacecraft crossed the

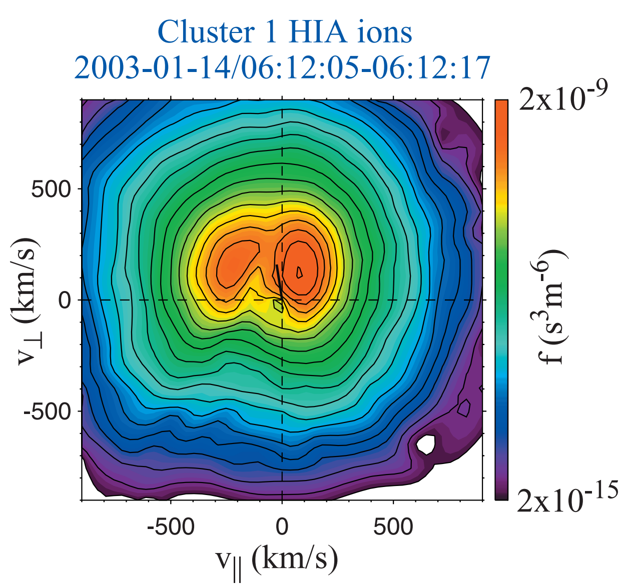

Figure 4. Two-dimensional cuts of a 3-D ion distributions inside the exhaust. The counterstreaming ion beams provide evidence for magnetic connection across the exhaust.

exhaust at a location where the exhaust width was ~10 ion skin depths.

4. ACE and Wind Observations of a Non-Reconnecting Current Sheet in the Solar Wind

[15] The same current sheet was detected in the upstream solar wind by ACE and Wind, but without any reconnection signatures. Because of the proximity of ACE to the Sun-Earth line, the ACE observations are most relevant for comparison with the Cluster-1 data.

[16] Figures 3f–3i shows the ACE observations of the current sheet near L1, shifted in time by 4080s to line up with the Cluster current sheet. In contrast to the Cluster-1 magnetosheath observations, there was no evidence for a plasma jet (Figure 3h) or density compression (Figure 3i) within the current sheet at ACE; an indication that ACE did not detect reconnection signatures in the solar wind current sheet. The current sheet crossing duration at ACE was 51s, compared to 15s at Cluster-1. With the current sheet convecting at 372 km/s along its normal - GSE [0.93, −0.18, −0.32] - the current sheet width was 18970 km, or 264 ion skin depths. If one assumes that the current sheet detected at ACE is similar in thickness to the portion of the solar wind current sheet that was encountered by Cluster-1 downstream, this would imply that the current sheet was compressed in width by a factor of 36 (or 26 in terms of the ion skin depth) going from ACE (at L1) to Cluster-1. This implies that the compression must have occurred at both the bow shock and against the magnetopause.

[17] Wind, located 85 R_E dawnward of the Sun-Earth line, also detected the passage of the same current sheet (Figures 3j–3m), although the magnetic field variations across the current sheet at Wind were more complicated (less monotonic) and much more extended in time (Figure 3k). The complete field rotation at Wind took ~100 s (compared to 51s at ACE), corresponding to an even thicker current sheet. The 3s resolution Wind 3DP plasma data revealed no evidence for plasma jetting (Figure 3l) or density compression (Figure 3m) in the current sheet. We conclude that Wind also did not detect reconnection signatures in the solar wind current sheet.

5. Summary and Discussion

[18] On January 14, 2003, at ~06:12 UT, Cluster-1 detected the passage of a reconnection exhaust in the dayside magnetosheath, ~0.8 R_E from the magnetopause. The magnetic shear across the field reversal was 162°, corresponding to a 15% guide field. We now summarize the key findings and discuss their implications.

[19] (1) The evidence for reconnection consists of accelerated plasma flow, ion density and temperature enhancements and magnetic field depression in the exhaust, counterstreaming ion beams and a bifurcated current sheet. These fluid and kinetic signatures of reconnection are similar to those observed in solar wind exhausts [e.g., *Gosling et al.*, 2005].

[20] (2) The reconnection electric field (E_M) determined independently from plasma and electric field measurements was in the range of ~0.7 mV/m. The corresponding dimensionless reconnection rate, v_N/v_A, was ~0.07, i.e., in the range of fast reconnection.

[21] (3) The spacecraft crossing of the exhaust occurred in the vicinity of the diffusion region, evidenced by an exhaust width of only 10 ion skin depths and the presence of the Hall magnetic field. More importantly, the fact that the Hall magnetic field profile was steepest, i.e., no gap, in the middle of the exhaust suggests that Cluster-1 actually crossed the ion diffusion region. The lack of a gap in B_M at a location where the exhaust width was rather thick (~10 ion skin depths) appears inconsistent with earlier simulations [e.g., *Shay et al.*, 1999] which showed the confinement of the Hall field to the separatrices at this location. However, more recent larger-scale particle simulations (M. A. Shay et al., Two-scale structure of the electron dissipation region during collisionless magnetic reconnection, submitted to *Physical Review Letters*, 2007) reveal a much longer ion diffusion region (along the outflow direction), extending beyond where the exhaust width is 10 ion skin depths, which could be consistent with the observed B_M structure.

[22] (4) The same current sheet was observed ~1 hour earlier by ACE and Wind in the upstream solar wind but without the embedded reconnection signatures. This indicates that the magnetosheath exhaust is not simply a solar wind reconnection exhaust convected into the magnetosheath. Hybrid [*Lin*, 1997] and MHD [*Maynard et al.*, 2002] simulations have suggested that reconnection could occur in the magnetosheath as a result of the compression of solar wind current sheets at the bow shock. Our finding of a thick (264 ion skin depths) current sheet in the solar wind and a 36 times thinner current sheet in the magnetosheath indicates that additional compression against the magnetopause must have occurred to reduce the current sheet width to the ion skin depth scales to set off reconnection. The compression against the dayside magnetopause is indeed expected in this case because the magnetic field on the leading edge of the exhaust was northward. It is possible that bow shock compression alone could trigger reconnection in other cases when the initial solar wind current sheets are thinner.

[23] (5) Although not shown in this paper, not all of the Cluster spacecraft detected reconnection signatures in the magnetosheath current sheet even though the spacecraft were less than 2 R_E apart. Cluster-2, which was located ~1 R_E (duskward) from Cluster-1, also detected a finite tangential (reconnection) electric field of ~0.5 mV/m. However, the Cluster-3 and 4 spacecraft, which were 2 R_E duskward and sunward of Cluster 1 and detected the current sheet 3 minutes earlier, did not detect plasma acceleration or the reconnection electric field. This suggests that reconnection was either limited in spatial extent or was initiated within the 3 minutes between the time spacecraft 3–4 and spacecraft 1–2 encountered the current sheet. Detailed findings on the 4 Cluster spacecraft measurements will be presented in a future paper.

[24] The event discussed here, together with a recently reported reconnection event in a current sheet generated by magnetosheath turbulence [*Retino et al.*, 2007], demonstrates that the magnetosheath is another region in space where reconnection occurs. Just as the recently recognized solar wind reconnection exhausts made it possible to detect the enormous spatial scales on which reconnection can

occur as well as the steadiness of the process, magnetosheath reconnection events may shed light on the onset and (temporal and spatial) evolution of reconnection.

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