

Development of bifurcated current sheets in solar wind reconnection exhausts

Short title: Bifurcations at solar wind exhausts

Authors

R. Mistry¹, J. P. Eastwood¹, T. D. Phan², H. Hietala¹

¹ Space and Atmospheric Physics, Blackett Laboratory, Imperial College London, London, UK

² Space Sciences Laboratory, University of California, Berkeley, California, USA

Key points

1. 3 events where both of the oppositely directed exhausts are observed
2. Exhausts encountered further from the X-line show clear bifurcations
3. Bifurcations may be fully developed ~1000 ion skin depths downstream

Abstract

Petschek-type reconnection is expected to result in bifurcations of reconnection current sheets. In contrast, Hall reconnection simulations show smooth changes in the reconnecting magnetic field. Here we study three solar wind reconnection events where different spacecraft sample oppositely directed reconnection exhausts from a common reconnection site. The spacecraft's relative separations and measurements of the exhaust width are used to geometrically calculate each spacecraft's distance from the X-line. We find that in all cases spacecraft furthest from the X-line observe clearly bifurcated reconnection current sheets, while spacecraft nearer to the X-line do not. These observations suggest that clear bifurcations of reconnection current sheets occur at large distances from the X-line (~ 1000 ion skin depths), and that Petschek-type signatures are less developed close to the reconnection site. This may imply that fully developed bifurcations of reconnection current sheets are unlikely to be observed in the near-Earth magnetotail.

Introduction

The process of magnetic reconnection changes the magnetic topology within plasmas, and converts magnetic energy into thermal and kinetic energy. However, for it to play a physically important role, it is generally considered that the rate of reconnection must be fast; this was a key criticism of early reconnection models (e.g., *Parker* [1957], *Sweet* [1958]). *Petschek* [1964] proposed that the reconnection rate could be enhanced for anti-parallel reconnection if the diffusion region was reduced in size and if the majority of plasma passed through slow-mode shocks along the edges of two oppositely directed exhausts of accelerated plasma outflow. The slow shocks increase the plasma density and temperature within the exhaust. Another key characteristic of Petschek reconnection is a bifurcation of the current sheet. This results in the reconnecting component of the magnetic field (B_L) changing abruptly in two steps. Across one boundary B_L changes from a positive value to zero within the exhaust, and across the other boundary B_L changes from zero to a negative value.

A criticism of the Petschek model is that it requires a region of enhanced resistivity at the diffusion region, otherwise the solution relaxes to a Sweet-Parker type configuration (e.g., *Erkaev et al.* [2000]). However, such models are based on single fluid magnetohydrodynamics. It is now understood that two-fluid effects are essential to fast reconnection for conditions typically seen in Earth's magnetosphere and the solar wind. This leads to a two-scale diffusion region, with characteristic out-of-plane Hall magnetic fields [*Birn et al.*, 2001; *Drake et al.*, 2008; *Mandt et al.*, 1994]. Although slow-mode changes in density/temperature have been shown to develop in hybrid reconnection simulations, current sheet bifurcations are not clear (e.g., *Higashimori and Hoshino* [2012], *Lottermoser et al.* [1998] and references therein); the field changes more smoothly across the exhaust. Similarly, the majority of kinetic Particle-In-Cell (PIC) simulations produce smooth changes in the field instead of bifurcated current sheets. For example, *Liu et al.* [2012] showed that in a large-scale 2.5D PIC simulation of anti-parallel reconnection large ion temperature anisotropies develop and push the exhaust towards becoming firehose unstable, preventing the formation of slow shocks and current sheet bifurcations. Such large anisotropy has been observed for near-anti-parallel reconnection in the magnetotail [*Hietala et al.*, 2015]. However, it has been shown that with the introduction of a weak guide field (0.3 of the reconnecting field) to suppress the firehose instability, slow shocks and current sheet bifurcations can form in a PIC simulation at $\sim 130 d_i$ from the X-line, after a long simulation time (40 ion gyroperiods) [*Innocenti et al.*, 2015].

The presence of the ion diffusion region in the magnetotail is well documented (e.g., *Eastwood et al.* [2010]), but during magnetotail reconnection events spacecraft often remain within the exhaust for tens of minutes (e.g., *Angelopoulos et al.* [1992]). This makes it difficult to unambiguously determine the spacecraft location within the exhaust, and whether the current sheet is bifurcated, particularly in single spacecraft observations. Nevertheless, bifurcated current sheets have been observed at Earth's magnetotail and have been suggested to be associated with Petschek-type exhausts [*Asano et al.*, 2005; *Hoshino et al.*, 1996]. They have also been suggested to be associated with wave-like transients (e.g., *Runov et al.* [2003a]) and instabilities (e.g., *Daughton et al.*

[2004], *Ricci et al.* [2004]). The formation mechanism of bifurcated current sheets in the magnetotail therefore remains unclear. Furthermore, whilst slow-mode shocks have been observed in the near/mid-Earth magnetotail [*Eriksson et al.*, 2004; *Øieroset et al.*, 2000], most magnetotail slow-mode shock observations (consistent with Petschek-type reconnection) are from the mid/deep tail using ISEE 3 and Geotail (e.g., *Feldman et al.* [1985], *Saito et al.* [1995], *Smith et al.* [1984]).

The spatial structure of exhausts can be more accurately studied in the solar wind, where exhausts are convected past spacecraft with the solar wind on short timescales. Spacecraft positions relative to exhausts can be accurately determined, allowing spatial properties of the exhaust to be identified unambiguously across the spacecraft track. Furthermore, the system in which reconnection occurs (the solar wind) is far larger than that for reconnection at a magnetosphere. Exhausts are therefore expected to form larger structures, where the outflow can continue to freely flow away from the reconnection site.

There have been multiple observations of bifurcated current sheets at solar wind exhausts (e.g., *Gosling et al.* [2005], *Gosling et al.* [2006], *Phan et al.* [2006]) and it has therefore become common to associate bifurcated solar wind current sheets with reconnection. There are, however, examples of solar wind reconnection current sheets which are not bifurcated (e.g., *Gosling* [2007], *Gosling et al.* [2007b], *Mistry et al.* [2015]). One may expect that nearer to the X-line Hall physics should dominate particle dynamics and current sheets should therefore have a similar profile to that obtained from hybrid/PIC simulations. However, whilst single spacecraft observations provide very clear information about structure across the exhaust, the distance to the X-line is essentially unknown. The exhaust width far from the X-line may vary as a result of its interaction with the solar wind, which may distort the exhaust geometry [*Mistry et al.*, 2015], or the exhaust may stop expanding at significantly large distances from the X-line.

At the magnetotail/magnetopause the X-line can only exist within a limited and well defined space (which spacecraft orbits can be tuned to intercept), whereas solar wind X-lines can exist in a

much larger space. It is therefore much less likely that the X-line would be located in between different spacecraft that observe the same event in the solar wind. If both of the oppositely directed exhausts are observed by different spacecraft, the reconnection geometry can be constrained much more precisely. *Davis et al.* [2006] presented such observations using ACE and Wind, showing that both spacecraft were located far from the reconnection site ($\sim 9000 d_i$), and both observed bifurcated current sheets.

Here we study the magnetic structure of three rare reconnection observations where different spacecraft observe oppositely directed solar wind exhausts from a common reconnection site. As both sides of the X-line were observed, we can use constraints from spacecraft observations to estimate each spacecraft's distance from the X-line in the outflow direction, and the implied reconnection rate. In all three cases, we find that the spacecraft furthest from the reconnection site observes a clearly bifurcated current sheet in agreement with Petschek-type reconnection, whereas spacecraft closer to the reconnection site do not. This allows, for the first time, observational constraints to be placed on the distance from the X-line at which bifurcations of reconnection current sheets may form.

Observations

In this study we use Cluster, Wind and ACE data and use the highest available cadence from each spacecraft magnetometer (22 Hz, 11 Hz and 1 Hz, respectively) in order to resolve the detailed magnetic structure across the exhaust. We first surveyed Cluster solar wind data from 2009 for reconnection exhausts, then sought to identify the same events in Wind and ACE data. Three events were found where oppositely directed exhausts were observed. For each event, the data were transformed into hybrid minimum variance co-ordinates [Gosling and Phan, 2013] (shown in Table 1) based on magnetic field measurements at Cluster-1. The current sheet normal is $\mathbf{N} = (\mathbf{B}_1 \times \mathbf{B}_2) / |\mathbf{B}_1 \times \mathbf{B}_2|$ where $\mathbf{B}_1$ and $\mathbf{B}_2$ are magnetic field vectors either side of the current sheet. The out-of-plane

direction is $\mathbf{M} = \mathbf{N} \times \mathbf{L}'$, where $\mathbf{L}'$ is the maximum variance direction [Sonnerup and Cahill, 1967]. The exhaust outflow direction is $\mathbf{L} = \mathbf{M} \times \mathbf{N}$. Magnetic field and ion data are near identical at each Cluster spacecraft for all three events (note that no solar wind ion data is available from Cluster-2 and Cluster-4), so we show data from Cluster-1 only. For each event the predicted time interval between observations of a planar current sheet at each spacecraft ($\Delta N / (\mathbf{V}_{sw} \cdot \mathbf{N})$, where ΔN is the spacecraft separation along $\mathbf{N}$ in the spacecraft frame and $\mathbf{V}_{sw}$ is the solar wind velocity) is in excellent agreement with the observed interval (maximum difference of 5%, for event 1), and there are strong similarities in magnetic field and ion measurements between spacecraft, confirming that the spacecraft observe the same planar current sheet. Furthermore, the Walén relation (e.g., Paschmann et al. [1986]) shows that observations at each spacecraft are consistent with reconnection.

Figure 1 shows observations from 24th February 2009 (event 1). The current sheet at Cluster-1 is clearly bifurcated; at 08:53:47 UT and 08:54:25 UT there are sudden changes in B_L . B_L is approximately constant in between these times. The current sheet is accompanied by an increase in the ion velocity in the $+L$ direction, indicating a reconnection exhaust. Wind data show a smooth change in the magnetic field between 08:54:00 UT and 08:54:07 UT; the current sheet is clearly not bifurcated. This is associated with an increase in the ion velocity in the $-L$ direction. This event could not be found in ACE data. We conclude that the spacecraft observed oppositely directed exhausts from a common reconnection site located between the spacecraft.

If it is assumed that the exhaust has a constant opening angle, ϑ , (and therefore reconnection rate) both along the X-line and with increasing distance along the outflow, we can use the spacecraft separation along L and the observed exhaust width at each spacecraft to determine ϑ . The reconnection rate is $\tan(\vartheta/2)$. The exhaust widths $(\mathbf{V}_{sw} \cdot \mathbf{N})\delta t$, where δt is the observed exhaust duration) measured by Cluster-1 and Wind are 119 d_i and 12 d_i , respectively, where d_i is the ion skin depth using the mean ion density measured on either side of the exhaust by Cluster-1 (3.6 cm^{-3}).

Their separation in L in the exhaust's frame of reference is calculated to be $1295 d_i$. The observed widths indicate $\vartheta = 5.8^\circ$ (reconnection rate 0.05) and place the X-line at a distance of $1180 d_i$ from Cluster-1 and $116 d_i$ from Wind.

Figure 2 shows observations from 6 March 2009 (event 2). The current sheet at Cluster-1 is not bifurcated, and is associated with an exhaust in the $-L$ direction. At Wind the magnetic field undergoes several sharp changes and has a complex profile. Although there are sharp changes in B_L , B_L is not constant across the exhaust and we conclude that the current sheet is not clearly bifurcated. Ion velocity data indicate an exhaust in the $+L$ direction. At ACE the current sheet is clearly bifurcated. A plasma measurement within the current sheet shows accelerated flow in the $+L$ direction, consistent with the expected exhaust direction given the spacecraft locations. Following the same procedure as for event 1, the spacecraft observations and positions demonstrate that the X-line passed between Cluster and Wind, with ACE being further away from the X-line than Wind (and on the same side of the X-line). We estimate ϑ using observations from Cluster-1 and Wind, from which ACE's distance from the X-line is inferred.

Finally, Figure 3 shows observations from 26 January 2009 (event 3). Cluster-1 observed a clearly bifurcated current sheet and an exhaust in the $+L$ direction. The Wind observations are more complex. There are abrupt changes in B_L at 17:47:25 UT and 17:47:47 UT, however in between these times B_L is not constant and gradually increases. Therefore, although the current sheet displays bifurcated characteristics, we conclude that the bifurcation is not fully developed. Ion velocity data indicate an exhaust in the $-L$ direction, again indicating that the X-line passed between Cluster and Wind. The presence of this event in ACE data was ambiguous, as the event duration was less than the temporal resolution of plasma measurements.

Table 1 summarises the properties of each event. Temperature enhancements are not observed at any of these events, and density enhancements are observed at both bifurcated exhausts (ACE event 2, and Cluster-1 event 3) and non-bifurcated exhausts (Wind events 1 and 3). Although slow-

mode shocks are expected to increase the density and temperature, many bifurcated exhausts have been observed with the absence of these signatures in the solar wind (e.g., *Gosling [2007], Gosling et al. [2007a]*).

Summary and Discussion

We have determined each spacecraft's separation from the X-line in the outflow (L) direction using measurements of the macro-scale reconnection geometry. This assumes that θ (and the reconnection rate) is constant with increasing distance from the X-line (along the outflow) and also along the X-line. We can estimate θ using this method as the detection of oppositely directed exhausts indicates that both spacecraft are relatively close to the X-line. Figure 4 shows the spacecraft separations along the X-line and their estimated distance from the X-line in the L - M plane. Spacecraft separations along the X-line are relatively small for event 1, however they are larger for event 2 (4984 d_i) and event 3 (6679 d_i). Variable reconnection rates along the X-line could affect the observed exhaust width at each spacecraft and could therefore account for some of the differences between observations at each spacecraft, however without large-scale 3D simulations it is difficult to assess the extent to which this may be important for observations such as these.

The reconnection rate can in principle be independently estimated from local measurements of differences in V_N on either side of the exhaust (ΔV_N), however ΔV_N is typically very small and difficult to determine. At Cluster-1 for event 3, $\Delta V_N = 4.6 \text{ km s}^{-1}$ (Figure 3(g)). This is consistent with plasma flowing into the exhaust (at 2.3 km s^{-1}) and a reconnection rate of 0.08, using the L component of the external Alfvén speed (29.6 km s^{-1}). This agrees with measurements of the reconnection rate from the macro-scale geometry (0.07). For all other spacecraft, however, we find that ΔV_N is negligible and we are unable to determine the reconnection rate using this method.

Alternatively, multi-spacecraft timing analysis across planar magnetic discontinuities can be used to determine discontinuity normals [*Dunlop and Woodward, 1998*]. The two sudden changes in

magnetic field across bifurcated current sheets can be treated as such discontinuities. To accurately estimate the normals (and associated errors) we take a Monte Carlo approach, where we identify a time interval in which each Cluster spacecraft crosses one of the bifurcations. We apply timing analysis to randomly selected times from each spacecraft's identified interval, repeating the process 1000 times. For event 1 the difference in boundary normals is $2.4 \pm 12.1^\circ$. The large error is because the interval over which B_L changes (~ 4.8 s) is not significantly smaller than time delays between observations at each spacecraft (~ 10 s), and indicates that the measurement is not reliable. For event 3 the difference in boundary normals is $10.6 \pm 5.6^\circ$, however their orientation is such that they would diverge as they approach the reconnection site (instead of converge), therefore the reconnection rate cannot be estimated. In both cases Cluster was in a regular tetrahedral arrangement with inter-spacecraft separations of $\sim 10,000$ km (event 1) and $\sim 30,000$ km (event 3). This method cannot be used for event 2 as Cluster did not observe a bifurcated current sheet. This indicates that the reconnection rate may be more reliably determined from the macro-scale geometry using spacecraft on opposite sides of the X-line, instead of local measurements which may have considerable uncertainty, and which may be affected by local fluctuations in reconnection dynamics.

In all three events, despite observing the same reconnection event, different spacecraft observe characteristically different magnetic field profiles. Moreover, in each event the spacecraft furthest from the reconnection site observe fully developed bifurcations of the current sheet, while those closer to the reconnection site do not. This indicates that bifurcations of reconnection current sheets form with increasing distance from the X-line. In the *Davis et al.* [2006] event both spacecraft observed a bifurcated current sheet and were both significantly further from the X-line ($8500 d_i$ and $9800 d_i$ for Wind and ACE, respectively, shown in Figure 4) than the spacecraft in the present study (maximum of $4958 d_i$), so this observation is apparently consistent with our results.

Figure 4 indicates that current sheet bifurcations become clear at distances greater than $\sim 1000 d_i$ from the X-line. The events in this study have guide fields of 0.27-1.92 of the reconnecting field

(Table 1) and ion beta of the order 1. If this result is applied to the magnetotail, 1000 d_i corresponds to 50-160 R_E for plasma densities of 0.05-0.5 cm^{-3} . This suggests that fully developed bifurcations of large-scale exhausts should not develop in the near-Earth tail, but that they could form in the mid/deep magnetotail. Interestingly, most reports of slow shocks in the magnetotail are from ISEE 3 and Geotail observations, also in the mid/deep tail (e.g., *Feldman et al.* [1985], *Saito et al.* [1995], *Smith et al.* [1984]). Magnetotail reconnection, however, typically has near anti-parallel magnetic fields and low plasma beta. We note that *Innocenti et al.* [2015] reported slow-mode shocks at $\sim 130 d_i$ from the X-line in PIC simulations with a guide field of 0.3, however it is not known how this distance changes with more realistic mass ratios and plasma temperatures. Additionally, in pure anti-parallel reconnection large ion temperature anisotropies prevent the formation of slow shocks [*Liu et al.*, 2012]. A more extensive survey of the effects of guide fields and plasma parameters on the formation of current sheet bifurcations and slow-mode shocks is therefore required. Enhanced current densities that are not in the center of ion [*Nakamura et al.*, 2002; *Runov et al.*, 2003b] and electron [*Wygant et al.*, 2005] scale magnetotail current sheets have been reported close to diffusion regions, however these are kinetic scale structures which differ from those which we present.

Our results indicate that bifurcations appear with increasing distance from the reconnection site. In these observations the X-line was located between the spacecraft. It is far more common, however, for spacecraft to be located on the same side of the X-line and very far from the reconnection site, because of the large size of solar wind exhausts. In all such observations, however, the distance to the X-line is essentially unknown. We note that it is not clear how exhausts behave at very large distances from the X-line, and whether they collimate or how they interact with the solar wind (for example, some single spacecraft observations of relatively thin exhausts show bifurcated current sheets, and some relatively thick exhausts show non-bifurcated current sheets). This warrants further investigation into the dynamics of exhausts at large distances from the reconnection site.

Figures

Table 1 Spacecraft measurements, their locations relative to Cluster-1, and calculated parameters. LMN coordinates are expressed in terms of Geocentric Solar Ecliptic coordinates.

	Event 1			Event 2			Event 3		
	Cluster-1	Wind		Cluster-1	Wind	ACE	Cluster-1	Wind	
Magnetic shear, °	138	121		59	60	55	150	145	
Guide field	0.38	0.57		1.77	1.73	1.92	0.27	0.32	
L component of Alfven speed, km s⁻¹	39.3	34.9		21.1	24.3	21.1	29.6	33.5	
Density, cm⁻³	3.6	3.0		4.6	3.3	3.9	14.4	10.8	
d_i, km	119	131		107	125	116	60	69	
Duration, s	61.5	6.0		28.2	55.9	120.4	141.5	21.9	
Exhaust width, d_i	119	12		36	71	269	715	111	
L separation, d_i	-	1295		-	613	1754	-	5726	
M separation, d_i	-	1092		-	3655	4984	-	6679	
Distance to X-line, d_i	1180	116		206	408	1548	4958	768	
θ, °	5.8			9.9			8.3		
Reconnection rate	0.05			0.09			0.07		
L (x,y,z)	0.25	0.31	0.92	0.05	0.79	0.61	0.45	0.58	0.68
M (x,y,z)	-0.86	-0.38	0.36	0.91	-0.29	0.30	0.03	-0.77	0.63
N (x,y,z)	0.46	-0.87	0.17	0.42	0.53	-0.73	0.89	-0.26	-0.37

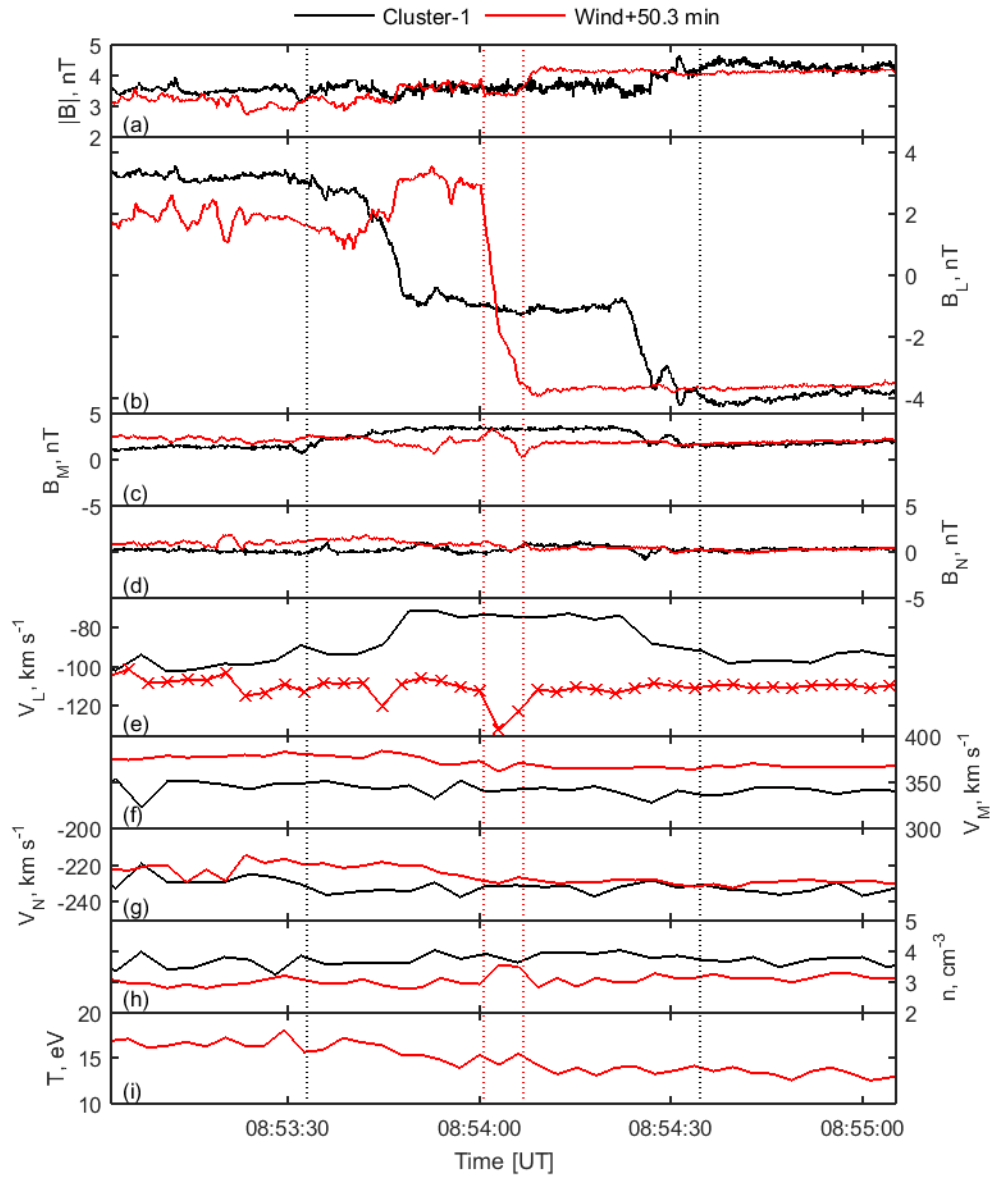


Figure 1 Event 1 measurements (in the spacecraft frame) of (a-d) magnetic field and (e-g) ion velocity, in LMN coordinates, (h) ion density, and (i) ion temperature (Wind only). Vertical lines indicate the time at which the exhaust is observed by each spacecraft.

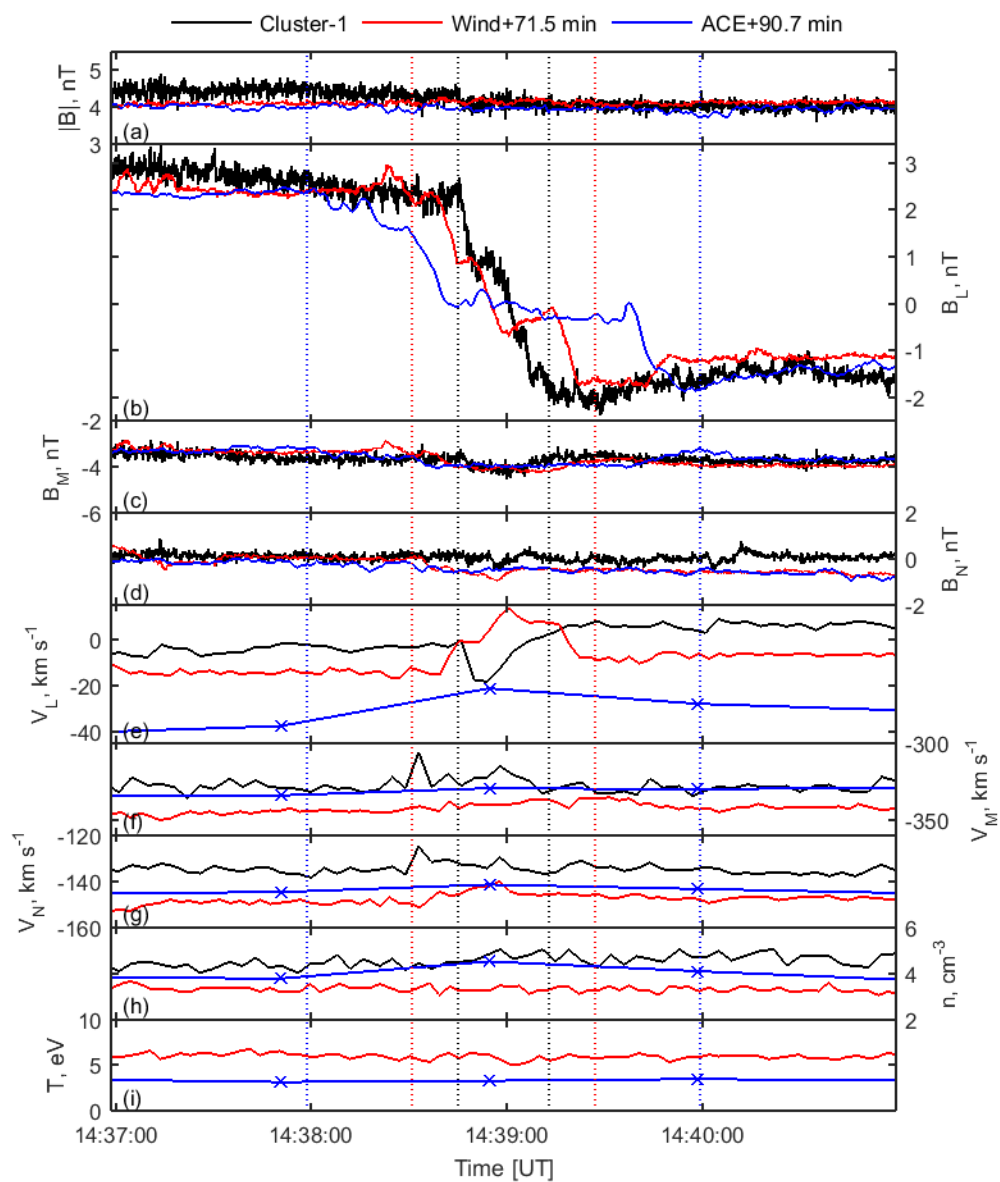


Figure 2 Event 2 observations in the same format as Figure 1.

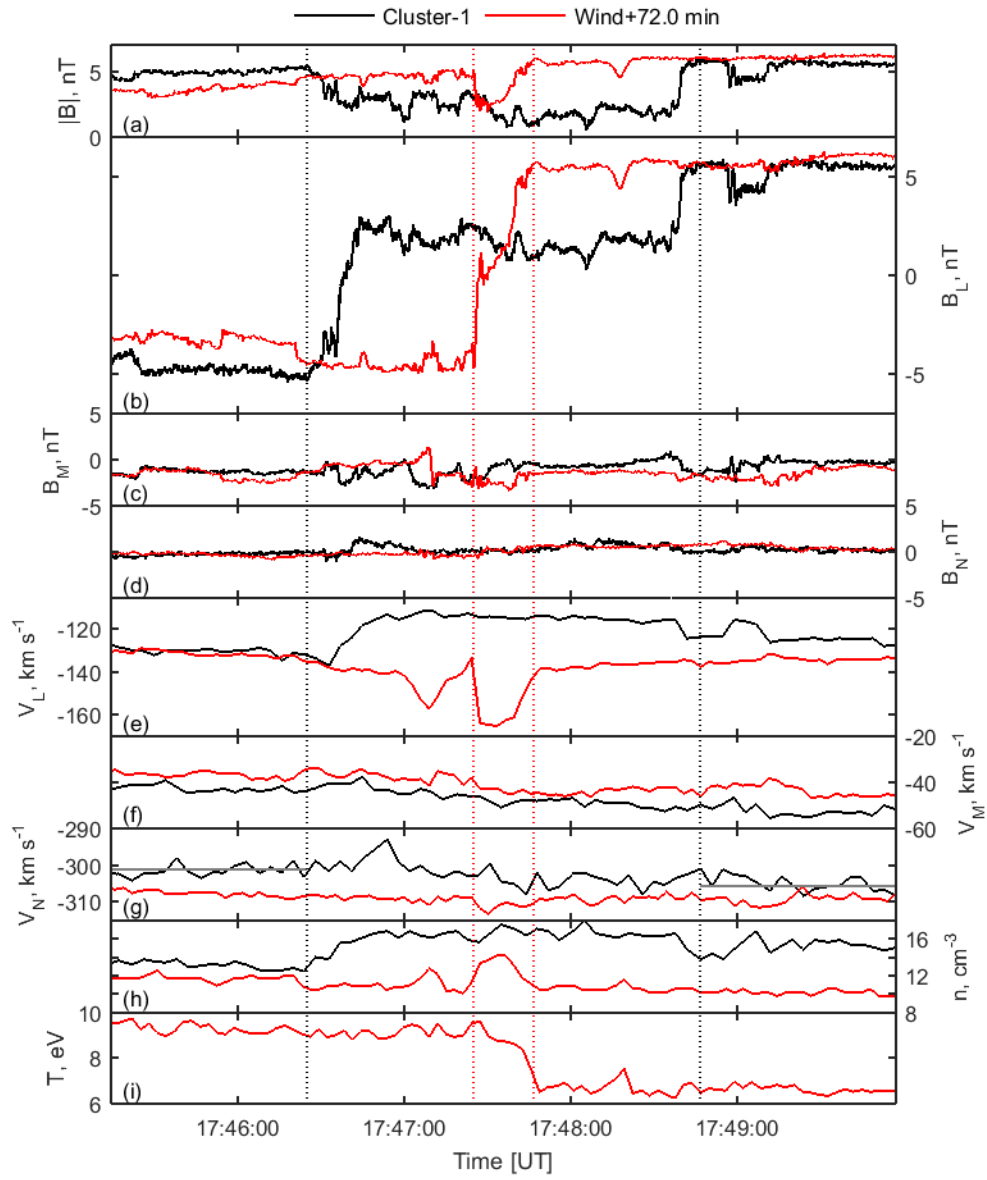


Figure 3 Event 3 observations in the same format as Figure 1. Horizontal lines in (g) indicate average V_N at Cluster-1 before and after the exhaust.

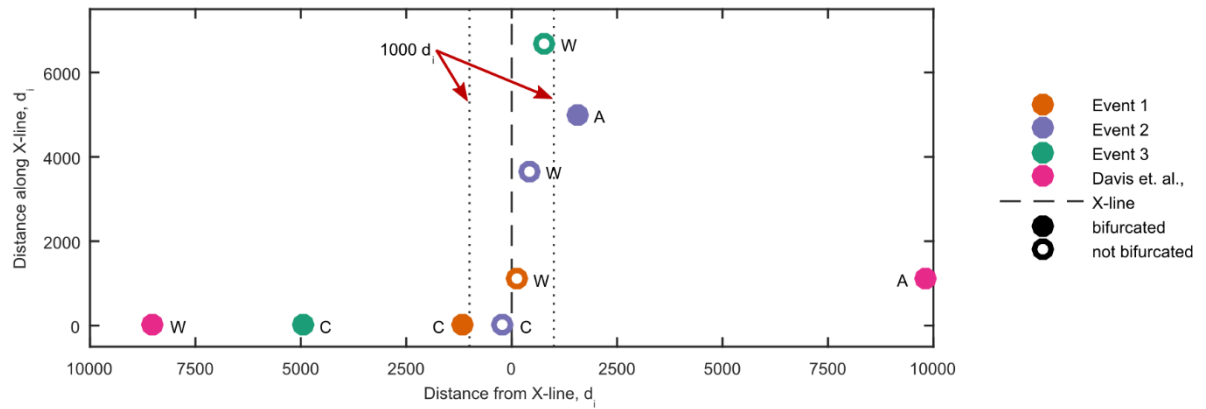


Figure 4 Spacecraft's estimated distance from the X-line along L (x-axis) and separation along the X-line from other spacecraft that observed the same event (y-axis). The *Davis et al.* [2006] event is also shown. Cluster (C) (and Wind (W) for *Davis et al.* [2006] event only) are shown on the left of the X-line. Spacecraft on the opposing side of the X-line are placed on the right hand side. Solid circles indicate observations of clearly bifurcated current sheets.

References

- Angelopoulos, V., W. Baumjohann, C. F. Kennel, F. V. Coroniti, M. G. Kivelson, R. Pellat, R. J. Walker, H. Lühr, and G. Paschmann (1992), Bursty bulk flows in the inner central plasma sheet, *Journal of Geophysical Research: Space Physics*, 97(A4), 4027-4039.
- Asano, Y., R. Nakamura, W. Baumjohann, A. Runov, Z. Vörös, M. Volwerk, T. L. Zhang, A. Balogh, B. Klecker, and H. Rème (2005), How typical are atypical current sheets?, *Geophysical Research Letters*, 32(3), L03108.
- Birn, J., et al. (2001), Geospace Environmental Modeling (GEM) Magnetic Reconnection Challenge, *Journal of Geophysical Research: Space Physics*, 106(A3), 3715-3719.
- Daughton, W., G. Lapenta, and P. Ricci (2004), Nonlinear Evolution of the Lower-Hybrid Drift Instability in a Current Sheet, *Physical Review Letters*, 93(10), 105004.
- Davis, M. S., T. D. Phan, J. T. Gosling, and R. M. Skoug (2006), Detection of oppositely directed reconnection jets in a solar wind current sheet, *Geophysical Research Letters*, 33(19), L19102.
- Drake, J. F., M. A. Shay, and M. Swisdak (2008), The Hall fields and fast magnetic reconnection, *Physics of Plasmas*, 15(4), 042306.
- Dunlop, M. W., and T. I. Woodward (1998), Multi-Spacecraft Discontinuity Analysis: Orientation and Motion, in *Analysis Methods for Multi-Spacecraft Data*, edited by G. Paschmann and P. W. Daly, ESA Publication Division, Netherlands.
- Eastwood, J. P., T. D. Phan, M. Øieroset, and M. A. Shay (2010), Average properties of the magnetic reconnection ion diffusion region in the Earth's magnetotail: The 2001–2005 Cluster observations and comparison with simulations, *Journal of Geophysical Research: Space Physics*, 115(A8), A08215.
- Eriksson, S., M. Øieroset, D. N. Baker, C. Mouikis, A. Vaivads, M. W. Dunlop, H. Rème, R. E. Ergun, and A. Balogh (2004), Walén and slow-mode shock analyses in the near-Earth magnetotail in connection with a substorm onset on 27 August 2001, *Journal of Geophysical Research: Space Physics*, 109(A10), A10212.
- Erkaev, N. V., V. S. Semenov, and F. Jamitzky (2000), Reconnection Rate for the Inhomogeneous Resistivity Petschek Model, *Physical Review Letters*, 84(7), 1455-1458.
- Feldman, W. C., D. N. Baker, S. J. Bame, J. Birn, J. T. Gosling, E. W. Hones, and S. J. Schwartz (1985), Slow-mode shocks: A semipermanent feature of the distant geomagnetic tail, *Journal of Geophysical Research: Space Physics*, 90(A1), 233-240.
- Gosling, J. T. (2007), Observations of magnetic reconnection in the turbulent high-speed solar wind, *The Astrophysical Journal Letters*, 671(1), L73.
- Gosling, J. T., and T. D. Phan (2013), Magnetic Reconnection in the Solar Wind at Current Sheets Associated with Extremely Small Field Shear Angles, *The Astrophysical Journal Letters*, 763(2), L39.
- Gosling, J. T., R. M. Skoug, D. J. McComas, and C. W. Smith (2005), Direct evidence for magnetic reconnection in the solar wind near 1 AU, *Journal of Geophysical Research: Space Physics*, 110(A1).
- Gosling, J. T., T. D. Phan, R. P. Lin, and A. Szabo (2007a), Prevalence of magnetic reconnection at small field shear angles in the solar wind, *Geophysical Research Letters*, 34(15), L15110.

299 Gosling, J. T., S. Eriksson, R. M. Skoug, D. J. McComas, and R. J. Forsyth (2006), Petschek-type
 300 reconnection exhausts in the solar wind well beyond 1 AU: Ulysses, *The Astrophysical Journal*,
 301 644(1), 613.

302 Gosling, J. T., S. Eriksson, D. J. McComas, T. D. Phan, and R. M. Skoug (2007b), Multiple magnetic
 303 reconnection sites associated with a coronal mass ejection in the solar wind, *Journal of Geophysical
 304 Research: Space Physics*, 112(A8), A08106.

305 Gosling, J. T., S. Eriksson, L. M. Blush, T. D. Phan, J. G. Luhmann, D. J. McComas, R. M. Skoug, M. H.
 306 Acuna, C. T. Russell, and K. D. Simunac (2007c), Five spacecraft observations of oppositely directed
 307 exhaust jets from a magnetic reconnection X-line extending $> 4.26 \times 10^6$ km in the solar wind at 1
 308 AU, *Geophysical Research Letters*, 34(20), L20108.

309 Hietala, H., J. F. Drake, T. D. Phan, J. P. Eastwood, and J. P. McFadden (2015), Ion temperature
 310 anisotropy across a magnetotail reconnection jet, *Geophysical Research Letters*.

311 Higashimori, K., and M. Hoshino (2012), The relation between ion temperature anisotropy and
 312 formation of slow shocks in collisionless magnetic reconnection, *Journal of Geophysical Research:
 313 Space Physics*, 117(A1), A01220.

314 Hoshino, M., A. Nishida, T. Mukai, Y. Saito, T. Yamamoto, and S. Kokubun (1996), Structure of plasma
 315 sheet in magnetotail: Double-peaked electric current sheet, *Journal of Geophysical Research: Space
 316 Physics*, 101(A11), 24775-24786.

317 Innocenti, M. E., M. Goldman, D. Newman, S. Markidis, and G. Lapenta (2015), Evidence of Magnetic
 318 Field Switch-off in Collisionless Magnetic Reconnection, *The Astrophysical Journal Letters*, 810(2),
 319 L19.

320 Liu, Y.-H., J. F. Drake, and M. Swisdak (2012), The structure of the magnetic reconnection exhaust
 321 boundary, *Physics of Plasmas*, 19, 022110.

322 Lottermoser, R. F., M. Scholer, and A. P. Matthews (1998), Ion kinetic effects in magnetic
 323 reconnection: Hybrid simulations, *Journal of Geophysical Research: Space Physics*, 103(A3), 4547-
 324 4559.

325 Mandt, M. E., R. E. Denton, and J. F. Drake (1994), Transition to whistler mediated magnetic
 326 reconnection, *Geophysical Research Letters*, 21(1), 73-76.

327 Mistry, R., J. P. Eastwood, and H. Hietala (2015), Detection of small-scale folds at a solar wind
 328 reconnection exhaust, *Journal of Geophysical Research: Space Physics*, 120(1), 30-42.

329 Nakamura, R., et al. (2002), Fast flow during current sheet thinning, *Geophysical Research Letters*,
 330 29(23), 55-51-55-54.

331 Øieroset, M., T. D. Phan, R. P. Lin, and B. U. Ö. Sonnerup (2000), Walén and variance analyses of
 332 high-speed flows observed by Wind in the midtail plasma sheet: Evidence for reconnection, *Journal
 333 of Geophysical Research: Space Physics*, 105(A11), 25247-25263.

334 Parker, E. N. (1957), Sweet's mechanism for merging magnetic fields in conducting fluids, *Journal of
 335 Geophysical Research*, 62(4), 509-520.

336 Paschmann, G., I. Papamastorakis, W. Baumjohann, N. Sckopke, C. W. Carlson, B. U. Ö. Sonnerup,
 337 and H. Lühr (1986), The magnetopause for large magnetic shear: AMPTE/IRM observations, *Journal*
 338 *of Geophysical Research: Space Physics*, *91*(A10), 11099-11115.

339 Petschek, H. (1964), Magnetic Field Annihilation, *NASA Spec. Publ*(50), 425-439.

340 Phan, T. D., et al. (2006), A magnetic reconnection X-line extending more than 390 Earth radii in the
 341 solar wind, *Nature*, *439*(7073), 175-178.

342 Ricci, P., G. Lapenta, and J. U. Brackbill (2004), Structure of the magnetotail current: Kinetic
 343 simulation and comparison with satellite observations, *Geophysical Research Letters*, *31*(6), L06801.

344 Runov, A., R. Nakamura, W. Baumjohann, T. L. Zhang, M. Volwerk, H. U. Eichelberger, and A. Balogh
 345 (2003a), Cluster observation of a bifurcated current sheet, *Geophysical Research Letters*, *30*(2), 1036.

346 Runov, A., et al. (2003b), Current sheet structure near magnetic X-line observed by Cluster,
 347 *Geophysical Research Letters*, *30*(11), 1579.

348 Saito, Y., T. Mukai, T. Terasawa, A. Nishida, S. Machida, M. Hirahara, K. Maezawa, S. Kokubun, and T.
 349 Yamamoto (1995), Slow-mode shocks in the magnetotail, *Journal of Geophysical Research: Space*
 350 *Physics*, *100*(A12), 23567-23581.

351 Smith, E. J., J. A. Slavin, B. T. Tsurutani, W. C. Feldman, and S. J. Bame (1984), Slow mode shocks in
 352 the Earth's magnetotail: ISEE-3, *Geophysical Research Letters*, *11*(10), 1054-1057.

353 Sonnerup, B., and L. J. Cahill (1967), Magnetopause structure and attitude from Explorer 12
 354 observations, *Journal of Geophysical Research*, *72*(1), 171-183.

355 Sweet, P. A. (1958), The neutral point theory of solar flares, paper presented at Electromagnetic
 356 phenomena in cosmical physics.

357 Wygant, J. R., et al. (2005), Cluster observations of an intense normal component of the electric field
 358 at a thin reconnecting current sheet in the tail and its role in the shock-like acceleration of the ion
 359 fluid into the separatrix region, *Journal of Geophysical Research: Space Physics*, *110*(A9), n/a-n/a.

360

Acknowledgements

Cluster data presented here are available from Cluster Science Archive (www.cosmos.esa.int/web/csa). ACE and Wind data are available from CDAWeb (cdaweb.gsfc.nasa.gov). We thank J. Gosling and R. Skoug for providing ACE data for event 2. This work was supported by the Turboplasmas project, and UK STFC through the award of a studentship (R.M.), and grant ST/K001051/1 (J.P.E. and H.H.).