Development of bifurcated current sheets in solar wind reconnection exhausts

Short title: Bifurcations at solar wind exhausts

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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 ~130 d 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.
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 [Ériksson 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. Exhaussts 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 (~9000 d), 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 $N = (\mathbf{B}_1 \times \mathbf{B}_2)/|\mathbf{B}_1 \times \mathbf{B}_2|$ 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 \( (\Delta N / (N_{SW} \cdot \mathbf{N})) \), where \( \Delta N \) is the spacecraft separation along \( \mathbf{N} \) in the spacecraft frame and \( V_{SW} \) 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, \( \theta \), (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 \( \theta \). The reconnection rate is \( \tan(\theta/2) \). The exhaust widths \( (N_{SW} \cdot \mathbf{N})\delta t \), where \( \delta t \) 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. The observed widths indicate $\theta$ = 5.8° (reconnection rate 0.05) and place the X-line at a distance of 1180 d, from Cluster-1 and 116 d, 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 $\theta$ 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) and event 3 (6679 d). 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, $ΔV_N = 4.6 \text{ km s}^{-1}$ (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 Alfven 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°. The large error is because the interval over which \(B_L\) changes (~4.8s) is not significantly smaller than time delays between observations at each spacecraft (~10s), and indicates that the measurement is not reliable. For event 3 the difference in boundary normals is 10.6\(\pm\)5.6°, 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 ~10,000 km (event 1) and ~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, and 9800 d for Wind and ACE, respectively, shown in Figure 4) than the spacecraft in the present study (maximum of 4958 d), so this observation is apparently consistent with our results.

Figure 4 indicates that current sheet bifurcations become clear at distances greater than ~1000 d, 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, 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 ~130
higher X distances 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.

<table>
<thead>
<tr>
<th></th>
<th>Event 1</th>
<th>Event 2</th>
<th>Event 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cluster-1</td>
<td>Wind</td>
<td>Cluster-1</td>
</tr>
<tr>
<td>Magnetic shear, °</td>
<td>138</td>
<td>121</td>
<td>59</td>
</tr>
<tr>
<td>Guide field</td>
<td>0.38</td>
<td>0.57</td>
<td>1.77</td>
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<tr>
<td>L component of Alfvén speed, km s⁻¹</td>
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<td>34.9</td>
<td>21.1</td>
</tr>
<tr>
<td>Density, cm⁻³</td>
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<td>3.0</td>
<td>4.6</td>
</tr>
<tr>
<td>d, km</td>
<td>119</td>
<td>131</td>
<td>107</td>
</tr>
<tr>
<td>Duration, s</td>
<td>61.5</td>
<td>6.0</td>
<td>28.2</td>
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<tr>
<td>Exhaust width, d,</td>
<td>119</td>
<td>12</td>
<td>36</td>
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<tr>
<td>L separation, d,</td>
<td>-</td>
<td>1295</td>
<td>-</td>
</tr>
<tr>
<td>M separation, d,</td>
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<td>1092</td>
<td>-</td>
</tr>
<tr>
<td>Distance to X-line, d,</td>
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<td>206</td>
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<tr>
<td>θ, °</td>
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<td></td>
<td>9.9</td>
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<tr>
<td>Reconnection rate</td>
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<td></td>
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<tr>
<td>L (x,y,z)</td>
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<td>0.31</td>
<td>0.92</td>
</tr>
<tr>
<td>M (x,y,z)</td>
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<td>-0.38</td>
<td>0.36</td>
</tr>
<tr>
<td>N (x,y,z)</td>
<td>0.46</td>
<td>-0.87</td>
<td>0.17</td>
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</table>
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


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