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Prevalence of extended reconnection X-lines in the solar wind at 1 AU

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[1] A survey of Wind and ACE data has been performed to address the generality of previous reports of extremely extended reconnection X-lines in the solar wind. We have studied 51 events in which both Wind and ACE detected the same solar wind current sheets and one of the spacecraft observed a reconnection exhaust. In 50 of the 51 events, the other spacecraft also observed essentially the same reconnection signatures, and all but one of the jets pointed in the same direction at both spacecraft. In 7 of these cases, the X-line extended more than 100 Earth radii (or 10^4 ion skin depths). Our findings strongly indicate that reconnection X-lines in large-scale current sheets (with magnetic shear $>\sim 70°$) are fundamentally extended, and not patchy and randomly distributed in space. Finally, the extended reconnecting current sheets are typically highly planar, indicating no significant current sheet warping associated with the reconnection process. **Citation:** Phan, T. D., J. T. Gosling, and M. S. Davis (2009), Prevalence of extended reconnection X-lines in the solar wind at 1 AU, *Geophys. Res. Lett.*, *36*, L09108, doi:10.1029/2009GL037713.

1. Introduction

[2] Magnetic reconnection is a universal plasma process that converts magnetic energy into particle energy. The amount of energy conversion depends on the reconnection rate, duration of reconnection, and the extent of both the current sheet and the reconnection X-line. A large number of observations of reconnection in the Earth's magnetosphere and at Earth's magnetopause have indicated the possibility that reconnection is a process that is intrinsically patchy, with the X-line extending at most a few Earth radii even through the current sheet extent in the magnetotail may be much larger [e.g., *Nakamura et al.*, 2004].

[3] The recent realization of the abundance of reconnection exhausts in the solar wind [*Gosling et al.*, 2005, 2007a; *Gosling*, 2007] provides unprecedented opportunities to study the large-scale properties of reconnection because of the presence of large-scale current sheets with relatively stable boundary conditions in the solar wind, conditions that are rare in Earth's magnetosphere. In three separate case studies, multi-spacecraft observations of X-lines extending hundreds of Earth radii (tens of thousands ion skin depths) and reconnection lasting several hours (or thousands of ion gyroperiods) have been reported [*Phan et al.*, 2006; *Gosling et al.*, 2007b, 2007c]. While these examples clearly illustrate that reconnection can be large scale and quasi-steady, it remains unclear whether this is the preferred mode of reconnection in large-scale current sheets in the solar wind. It is the purpose of the present statistical study to investigate the generality of the finding of extended reconnection X-lines and to search for counterexamples where reconnection may not be extended.

2. Individual Examples

[4] In this section we show two examples to illustrate the identification of extended and non-extended reconnection events as well as the procedure for obtaining the minimum X-line length and duration.

2.1. A Reconnection Exhaust Seen by Both Spacecraft

[5] Figure 1 shows the 1997-11-23 event where the Wind and ACE spacecraft detected reconnection signatures associated with the same current sheet. The two spacecraft were separated by 26 R_E, 31 R_E, and 40 R_E, respectively, in the x_{GSE}, y_{GSE}, and z_{GSE} directions. ACE observations of this event have previously been presented in detail by *Gosling et al.* [2005]. The leading edge of the reconnection exhaust was encountered by ACE at ~12:20:08 UT and by Wind at ~12:52:28 UT. The reconnection exhausts (between the two vertical dashed lines) at both spacecraft are recognized in the data by the presence of roughly Alfvenic accelerated flows within the region where the field reversed direction, with the changes in **V** (Figures 1c and 1h) and **B** (Figures 1b and 1g) being correlated on one edge and anti-correlated on the other edge of the exhaust, consistent with Alfven waves propagating in opposite directions along **B** away from a reconnection site [*Gosling et al.*, 2005]. The proton density (Figures 1d and 1i) and temperature (Figures 1e and 1j) enhancements are additional signatures of this reconnection exhaust, as is the field magnitude depression (Figures 1a and 1f). The total magnetic field rotations across the exhaust were similar at the two spacecraft (150° at ACE and 155° at Wind) and were stable for more than 10 minutes on each side of the exhaust, which occurred within an interplanetary coronal mass ejection, ICME.

[6] The exhaust normal at Wind was determined from a minimum variance analysis of the magnetic field (MVAB) [*Sonnerup and Cahill*, 1967] across the entire exhaust and found to be (0.34, 0.02, −0.94) in GSE, i.e., at a large angle with respect to the Sun-Earth line. Using this normal and assuming that the exhaust was planar, the predicted temporal delay from ACE to Wind was 30.7 minutes, within ~100 s of the observed temporal delay and thus an error of about 5%. This good agreement confirms the accuracy of the exhaust normal as well as the planar nature of this large-scale exhaust. It also confirms that the two spacecraft detected passage of the same reconnection exhaust.

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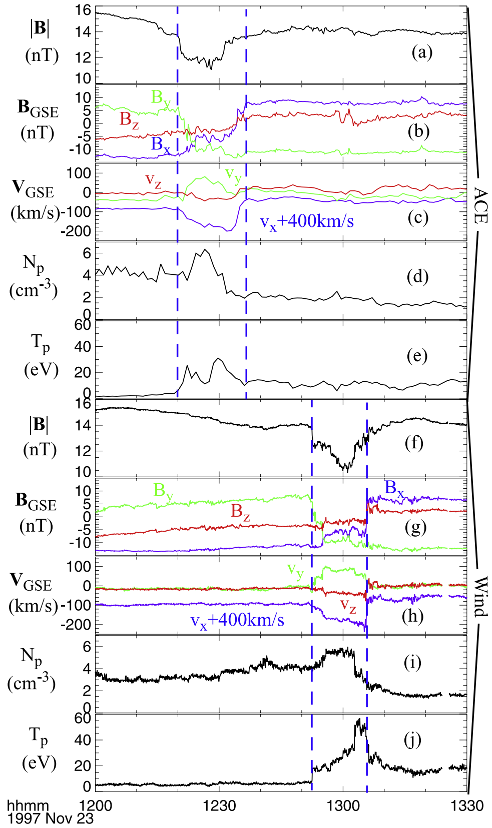

Figure 1. Detection of a reconnection exhaust by ACE (located at GSE [209, −47, −12] R_E) and Wind (located at GSE [183, −15, 28] R_E) on 1997-11-23. (a) The magnetic field magnitude, (b) the field components in GSE coordinates, (c) the plasma velocity components in GSE, (d) the proton density and (e) proton temperature measured by ACE; (f–j) Same as Figures 1a–1e but for Wind. The x component of the velocity in Figures 1c and 1h has been shifted by +400 km/s. Pairs of vertical dashed lines denote the 2 edges of the exhaust.

[7] The X-line orientation of (0.68, 0.68, 0.26) in GSE was also obtained from MVAB analysis as the direction of the intermediate variance. For nearly symmetric conditions on the two sides of the exhaust, this is the X-line direction predicted by the *Swisdak and Drake* [2007] model which maximizes the Alfvenic jet speed along the outflow direction. From this X-line orientation, one determines, based on the locations where Wind and ACE intersected the exhaust, that the two spacecraft detected reconnection flow from positions along the X-line that were 110 R_E apart (see Figure S1 in the auxiliary material).[1] This implies that the X-line was at least 110 R_E long.

[8] The fact that ACE and Wind encountered the exhaust ∼31 minutes apart suggests that reconnection was active at a distant X-line for at least that long sometime in the past, although it may not have been active at the time the exhaust was encountered by the spacecraft.

[9] Similar analyses were performed in previous studies of extended X-line events in the solar wind [*Phan et al.*, 2006; *Davis et al.*, 2006; *Gosling et al.*, 2007b, 2007c].

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL037713.

2.2. A Reconnection Exhaust Observed by Only One Spacecraft

[10] Figure 2 shows an example on 2005-01-11 where both Wind and ACE, separated by 64 R_E in GSE-y, detected the same current sheet, but only Wind clearly detected a reconnection exhaust.

[11] The characteristic flow acceleration (Figure 2h), proton density (Figure 2i) and temperature (Figure 2j) enhancements, and magnetic field depression associated with most reconnection exhausts were observed by Wind within a 162° field reversal region at 02:25–02:30 UT on this day. ACE detected a current sheet with similar shear angle of 170° and at almost the same time. The near-simultaneity of the current sheet encounter is consistent with the expected delay time of 3.6 minutes based on the geometry of the current sheet determined by the MVAB at Wind which yielded a normal of [0.78, −0.56, −0.29] GSE. However, the magnetic field profile and the thickness of the current sheet were different at the two spacecraft, with the current sheet being bifurcated (double-step field rotation) and much thicker at Wind than at ACE. More importantly, there was no evidence for reconnection jets, proton density and temperature enhancements, or a magnetic field strength depression in the current sheet encountered by ACE. Note that the 64-s resolution of the ACE plasma measurement should have been sufficient for ACE to have detected any accelerated flows during the 2-min crossing of the current sheet.

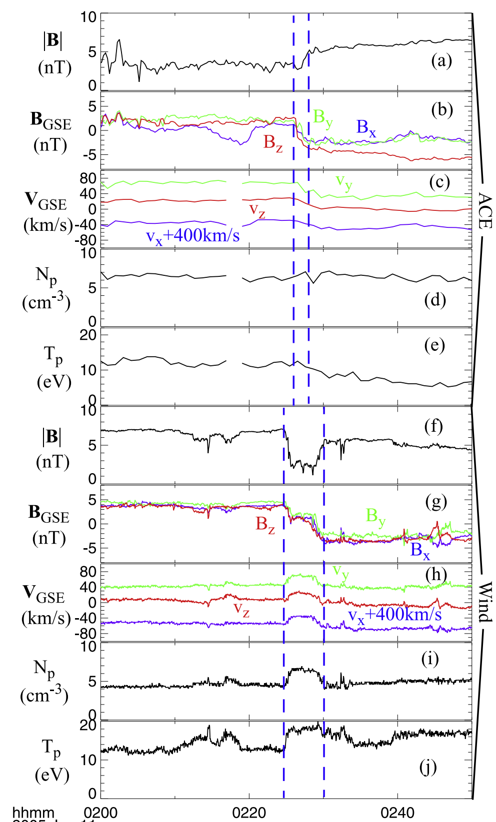

Figure 2. (a–j) Detection of a reconnection exhaust at Wind (located at GSE [255, 24, 20] R_E) but not at ACE (located at GSE [227, −40, 22] R_E) on 2005-01-11. The parameters are the same as in Figure 1.

[12] Finally, the fact that the current sheet at ACE was substantially narrower than at Wind is consistent with the absence of reconnection at ACE since the effect of reconnection is to bifurcate and broaden the pre-existing (i.e., prior to reconnection) current sheet with increasing distance from the X-line.

3. Statistical Survey

[13] In this section we search for the occurrence of large-scale current sheets in the solar wind and examine whether the X-line is commonly extended or not. We surveyed Wind and ACE solar wind observations from 1997 to 2005. We used 3s resolution plasma and magnetic field data from Wind and 16s resolution magnetic field and 64s resolution plasma measurements from ACE.

3.1. Selection Criteria

[14] We identified events where (1) both Wind and ACE detected the same solar wind current sheet, (2) both spacecraft were able to resolve the current sheet with plasma and field measurements (which means that the current sheet crossing at ACE had to be a bit longer than 64s), and (3) Wind observed the characteristic reconnection exhaust signature. We then examined whether ACE detected a reconnection exhaust as well. If in most of these events, reconnection signatures were detected by both spacecraft, irrespective of their separation, it would strongly suggest that reconnection in solar wind current sheets are commonly large scale and quasi-steady (at least on time scales up to a few hours). Common occurrence of reconnection seen by one spacecraft but not the other would favor patchy and/or intermittent reconnection.

[15] For this study we required that the 2 spacecraft detected the same current sheet because one cannot say anything about the extent of the X-line if the current sheet extent is smaller than the spacecraft separation. To ensure that the two spacecraft did indeed detect the same current sheet we selected only events where the magnetic fields on the two edges were stable (for at least 5 minutes) and that the magnetic field shear angle was similar (within $\sim 10^\circ$) at the two spacecraft. However, we did not require the field profile inside the current sheet to be the same since the structure of the current sheet itself (e.g., current sheet bifurcation) is probably dependent on the presence or absence of reconnection.

[16] To identify the reconnection exhaust we required the presence within the current sheet of (1) roughly Alfvenic accelerated flow, (2) depression of the magnetic field strength, (3) a proton density enhancement, and (4) a proton temperature enhancement that are characteristic of most exhausts [*Gosling et al.*, 2005]. These selection criteria ensure unambiguous identification of the exhaust even though they may be overly restrictive. For example, exhausts with large density or temperature asymmetry on the two sides of the current sheet often do not have density or temperature enhancements and would be discarded by our selection criteria. Similarly, exhausts with large field strength asymmetries often do not have field depressions and the requirement of longer than 64 s current sheet crossing duration at ACE necessarily excludes the very common narrow exhaust events often associated with small ($<40^\circ$) magnetic shear angles [*Gosling et al.*, 2007a]. Finally, the requirement that the magnetic field orientation on either side of the exhaust be stable for at least 5 minutes was a factor in eliminating events in the turbulent high-speed solar wind [e.g., *Gosling*, 2007].

3.2. Results

[17] 51 events were found which satisfied the above selection criteria, namely that both spacecraft detected the same current sheet and one of the spacecraft (Wind) detected a reconnection exhaust. Of these 51 events, a reconnection exhaust was also detected by ACE in 50 cases, the only exception being the 2005-01-11 event described in Section 2.2. We now proceed to determine the extent of the reconnection X-line and the ambient solar wind conditions associated with the 50 extended reconnection events. Details of all 51 events are given in Table S1 in the auxiliary material.

3.2.1. X-Line Extent and Reconnection Duration

[18] Before determining the X-line extent we first verify the validity of the planar current sheet assumption. Figure 3a shows the comparison between the predicted (assuming planar current sheets) and observed propagation times from ACE to Wind for the 50 events, where the orientation of the current sheet plane was determined by the MVAB across the exhaust at Wind. Negative lag times correspond to cases where the current sheets arrived at Wind before at ACE. The (94% on average) agreement between predicted and observed delay times is remarkable and implies that the large-scale current sheets in this data set were nearly planar up to a scale of hundreds of Earth radii. In contrast, partial entries into exhausts such as in the event discussed by *Gosling et al.* [2007b] suggest that small localized departures from planarity sometimes do exist.

[19] For each of the 50 events, we also determined the X-line orientation associated with the exhaust at Wind. From the X-line orientation, we determined, based on the locations where Wind and ACE intersected the exhaust, the minimum X-line extent. The minimum length that can be measured by the 2 spacecraft is largely a function of the spacecraft separation along GSE-y and z as well as the X-line orientation. The minimum X-line lengths for the 50 events, shown in Figure 3b, ranged from 1.6 R_E to 389 R_E.

[20] The minimum duration of reconnection is the time between the encounter of the leading edge of the exhaust by the first spacecraft and the encounter of the exhaust trailing edge by the second spacecraft. The durations of the 50 events ranged from 5.5 to 150 minutes. Note that since the exhaust crossings generally occur at large distances from the X-lines, reconnection at the X-line itself may or may nor be active during the times of the exhaust encounters, but it must have been active for a period of time before.

3.2.2. Ambient Solar Wind Conditions Surrounding the 50 Extended X-Line Events

[21] The magnetic shear angles across the 50 exhausts ranged from 68° to 175°, with more than 90% of the events having shear angles $>90^\circ$ (Figure 3d). The scarcity of low-shear events at first seems surprising since a large number of very low-shear angle (down to 15°) solar wind exhausts have been identified in the Wind data set [*Gosling et al.*, 2007a; *Gosling*, 2007; *Gosling and Szabo*, 2008]). However, low-shear angle exhausts tend to be relatively narrow ($<\sim 4 \times 10^4$ km) due to low reconnection rates [*Sonnerup*, 1974] and usually cannot be resolved by the 64 s resolution of the ACE

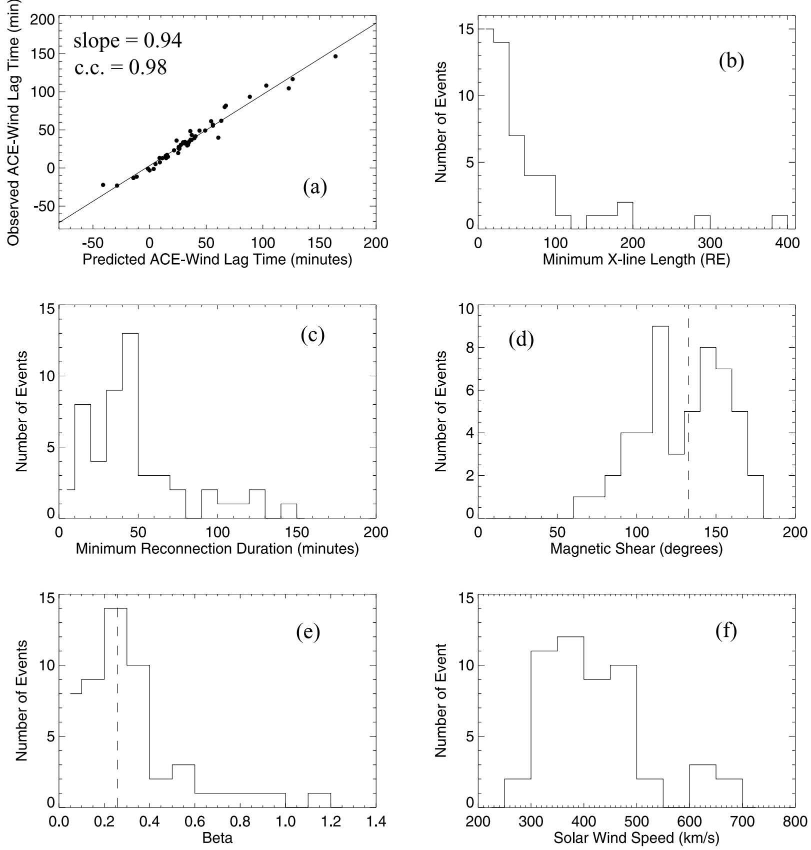

Figure 3. (a) Observed versus predicted propagation time from ACE to Wind of 51 solar wind current sheets. The distributions of (b) the minimum X-line length, (c) the minimum reconnection durations, (d) the full magnetic field rotations across the exhausts, (e) the proton β and (f) speeds of the inflow solar wind for the 50 events in which both ACE and Wind detected a reconnection exhaust. The ambient solar wind β and speed shown in Figures 3e and 3f are the averages of the values in the two inflow regions.

plasma measurement. Such small shear angle events would therefore be largely excluded from the present survey.

[22] Figure 3e shows the distribution of the average of the plasma β in the two inflow regions. All events have low β values, with β ranging from 0.04 to 1.18 and a median value of 0.25, which is considerably lower than the overall median β value for all of the solar wind [e.g., *Feldman et al.*, 1977].

[23] Figure 3f shows the distribution of the average of the ambient solar wind speed on the two sides of the exhaust. The solar wind speed ranged from 283 km/s to 670 km/s, with the majority of events having speeds below 500 km/s. Close examination of each event (see Table S1 in the auxiliary material) shows that all 7 events with speeds > 500 km/s were associated with ICMEs, i.e., none were associated with turbulent high-speed solar wind from coronal holes. In fact, at least 25 of the events occurred either within or at the edges of ICMEs and an additional 2 events occurred in the compressed sheaths ahead of ICMEs. Most of the remainder of the events occurred in the low-speed wind (V < 400 km/s), with 2 of those events occurring at the heliospheric current sheet (HCS). In other words, most of our set of extended X-line events did not occur at the heliospheric current sheet nor in the compressed sheaths ahead of ICMEs as one might naively have expected.

[24] With the exception of the event on 2003-01-03 [*Davis et al.*, 2006] in which oppositely-directed reconnection jets emanating from an X-line between ACE and Wind were detected, ACE and Wind detected reconnection jets pointing in the same direction in all other events in this data set. Note that there has been only one other reported detection of the oppositely directed jets from a reconnection site (on 2007-03-11) [*Gosling et al.*, 2007c]. That second event lies outside the time frame of the present study.

[25] Finally, the conditions surrounding the seemingly non-extended event (described in Section 2.2) do not seem be significantly different from the extended X-line events in terms of the ambient solar wind speed, β, the magnetic shear, or the distance between the 2 spacecraft. Thus the cause for this apparent short X-line is still unknown.

4. Discussion

[26] In this paper, we addressed the question of whether reconnection in the solar wind is commonly large scale or patchy. We surveyed 51 events in which both Wind and ACE detected the same large-scale current sheet and one of the spacecraft (Wind) observed a reconnection exhaust in the current sheet. We then asked whether ACE also detected the exhaust. We find that, with the exception of one event, reconnection exhausts were detected by both spacecraft,

irrespective of the spacecraft separation (of up to 288 R_E in y_{GSM}). This finding strongly indicates that the reconnection X-lines in large-scale current sheets in the solar wind are fundamentally extended. Furthermore, we find that, in 49 of the 50 extended X-line reconnection events, both spacecraft detected jets pointing in the same direction, which is consistent with the presence of a dominant X-line far from both spacecraft rather than a distribution of patchy and randomly distributed X-lines. The only bi-directional jet event in the present data set [*Davis et al.*, 2006] was consistent with a single X-line located between the spacecraft rather than the presence of two separate X-lines located exterior to the spacecraft pair.

[27] The 50 extended reconnection events in this survey occurred at rather large (>68°) magnetic shear angle current sheets and none occurred in the turbulent high-speed solar wind. The former is likely due to our selection criteria of minimum current sheet crossing duration of 64s which excludes most of the low-shear angle exhausts that tend to be narrow and cannot be resolved by ACE. The latter is due in part to the requirement that the magnetic field orientation be stable for at least 5 minutes (to facilitate the identification of the same current sheets at the 2 spacecraft) and also probably in part because current sheets in the turbulent high-speed wind tend to have smaller spatial extents. Thus the findings in the present survey are biased toward large magnetic shear angle (small guide field) reconnection, with the guide field to anti-parallel field ratio <1.4. Future studies should investigate whether the same conclusion holds for the very common low shear angle reconnection events [*Gosling et al.*, 2007a] as well.

[28] The general finding at 1 AU of seemingly coherent X-lines extending hundreds of Earth radii (tens of thousands of ion skin depths) is perhaps not unexpected theoretically. *Hesse et al.* [2001] found in 3D full particle simulations that initially random patchy reconnection structures in 3D reconnection tend to merge to form an extended reconnection structure resulting in essentially 2D reconnection. The X-line expansion could proceed at a significant fraction of the ion Alfven speed in anti-parallel reconnection [*Shay et al.*, 2003; *Lapenta et al.*, 2006] but could proceed at a much faster rate (up to the electron thermal speed) in the presence of a guide field. Thus it would take only 3 hours for an X-line to expand by 100 Earth radii in the anti-parallel case or only 5 minutes if the expansion rate is at the electron speed. Since the solar wind convection time from the Sun to 1 AU is ~4 days, a short X-line that is initiated considerably closer to the Sun can be extremely long by the time it reaches 1 AU, even without taking into account the transverse expansion of the solar wind, which stretches an X-line in the transverse to the radial direction with increasing heliocentric distance.

[29] Finally, the extended reconnecting current sheets are found to be exceptionally planar and are usually well represented by a single current sheet normal. This indicates that the large-scale solar wind current sheets are not twisted violently by reconnection, in contrast to the significant current sheet warping seen in 3D reconnection simulations involving electron-positron pair plasmas [*Yin et al.*, 2008].

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References

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, *Geophys. Res. Lett.*, *33*, L19102, doi:10.1029/2006GL026735.

Feldman, W. C., et al. (1977), Plasma and magnetic fields from the Sun, in *The Solar Output and Its Variation*, edited by O. R. White, p. 351, Colo. Assoc. Univ. Press, Boulder, Colo.

Gosling, J. T. (2007), Observations of magnetic reconnection in the turbulent high-speed solar wind, *Astrophys. J.*, *671*, L73, doi:10.1086/524842.

Gosling, J. T., and A. Szabo (2008), Bifurcated current sheets produced by magnetic reconnection in the solar wind, *J. Geophys. Res.*, *113*, A10103, doi:10.1029/2008JA013473.

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, *J. Geophys. Res.*, *110*, A01107, doi:10.1029/2004JA010809.

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, *Geophys. Res. Lett.*, *34*, L15110, doi:10.1029/2007GL030706.

Gosling, J. T., S. Eriksson, T. D. Phan, D. E. Larson, R. M. Skoug, and D. J. McComas (2007b), Direct evidence for prolonged magnetic reconnection at a continuous x-line within the heliospheric current sheet, *Geophys. Res. Lett.*, *34*, L06102, doi:10.1029/2006GL029033.

Gosling, J. T., S. Eriksson, L. M. Blush, T. D. Phan, J. G. Luhmann, D. J. McComas, R. M. Skoug, M. H. Acuna, C. T. Russell, and K. D. Simunac (2007c), Five spacecraft observations of oppositely directed exhaust jets from a magnetic reconnection X-line extending >4.26 × 10^6 km in the solar wind at 1 AU, *Geophys. Res. Lett.*, *34*, L20108, doi:10.1029/2007GL031492.

Hesse, M., M. Kuznetsova, and J. Birn (2001), Particle-in-cell simulations of three-dimensional collisionless magnetic reconnection, *J. Geophys. Res.*, *106*, 29,831, doi:10.1029/2001JA000075.

Lapenta, G., D. Krauss-Varban, H. Karimabadi, J. D. Huba, L. I. Rudakov, and P. Ricci (2006), Kinetic simulations of x-line expansion in 3D reconnection, *Geophys. Res. Lett.*, *33*, L10102, doi:10.1029/2005GL025124.

Nakamura, R., et al. (2004), Spatial scale of high-speed flows in the plasma sheet observed by Cluster, *Geophys. Res. Lett.*, *31*, L09804, doi:10.1029/2004GL019558.

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

Shay, M. A., J. F. Drake, M. Swisdak, W. Dorland, and B. N. Rogers (2003), Inherently three dimensional magnetic reconnection: A mechanism for bursty bulk flows?, *Geophys. Res. Lett.*, *30*(6), 1345, doi:10.1029/2002GL016267.

Sonnerup, B. U. Ö. (1974), Magnetopause reconnection rate, *J. Geophys. Res.*, *79*, 1546.

Sonnerup, B. U. Ö., and L. J. Cahill Jr. (1967), Magnetopause structure and attitude from Explorer 12 observations, *J. Geophys. Res.*, *72*, 171.

Swisdak, M., and J. F. Drake (2007), Orientation of the reconnection X-line, *Geophys. Res. Lett.*, *34*, L11106, doi:10.1029/2007GL029815.

Yin, L., et al. (2008), Three dimensional dynamics of collisionless magnetic reconnection in large scale pair plasmas, *Phys. Rev. Lett.*, *101*, 125001, doi:10.1103.

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