GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L20108, doi:10.1029/2007GL031492, 2007



# 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

J. T. Gosling,[1] S. Eriksson,[1] L. M. Blush,[2] T. D. Phan,[3] J. G. Luhmann,[3] D. J. McComas,[4] R. M. Skoug,[5] M. H. Acuna,[6] C. T. Russell,[7] and K. D. Simunac[8]

Received 27 July 2007; revised 28 August 2007; accepted 13 September 2007; published 25 October 2007.

[1] Observations of oppositely directed plasma jets within an extended, bifurcated current sheet in the solar wind by a flotilla of five well-separated spacecraft (STEREO A and B, ACE, Wind and Geotail) on 11 March 2007 demonstrate that magnetic reconnection X-lines in the solar wind can extend to distances at least as great as $4.26 \times 10^6$ km (0.0284 AU) in the presence of a significant and variable guide field. The observations also indicate that reconnection in the solar wind can persist for at least 5 hours and 20 minutes. These minimum values are the largest yet obtained from direct measurements of reconnection exhaust flows in a space plasma. Both dynamic processes in the reconnection region and the spherical expansion of the solar wind probably contribute to the production of long X-lines in the solar wind. **Citation:** 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 (2007), Five spacecraft observations of oppositely directed exhaust jets from a magnetic reconnection X-line extending > $4.26 \times 10^6$ km in the solar wind at 1 AU, *Geophys. Res. Lett.*, *34*, L20108, doi:10.1029/2007GL031492.

## 1. Introduction

[2] Magnetic reconnection is a plasma process that changes magnetic field topology and ultimately converts field energy to bulk flow energy and plasma heating. It occurs frequently at thin current sheets in the solar wind and produces Petschek-type exhausts, i.e., outflows of jetting plasma bounded by pairs of back-to-back rotational discontinuities [*Petschek*, 1964]. The exhausts are identified as roughly Alfvénic accelerated or decelerated plasma flows confined to field reversal regions that commonly take the form of bifurcated (double step) current sheets [e.g., *Gosling et al.*, 2005a]. The exhausts are embedded within the solar wind flow and are convected past a spacecraft on time scales ranging from a few seconds up to several hours. Near solar activity minimum a spacecraft in the solar wind upstream from Earth typically encounters 40–70 reconnection exhausts each month, the large majority of which are found in the low-speed wind, are associated with field rotations <90°, and are convected past a spacecraft in <100 s [*Gosling et al.*, 2007b]. In virtually all cases, two or more spacecraft are needed to detect the oppositely directed exhaust jets that result from reconnection in the solar wind; only one observation of such oppositely directed exhaust jets has thus far been reported [*Davis et al.*, 2006].

[3] Multi-spacecraft observations demonstrate that reconnection in the solar wind is commonly a quasi-stationary process that occurs at extended reconnection sites (X-lines). Observations made on 2 February 2002 within the interplanetary counterpart of a coronal mass ejection, ICME, provided evidence for an X-line that extended at least $2.5 \times 10^6$ km [*Phan et al.*, 2006]. In another case (31 August–1 September 2001), multi-spacecraft observations demonstrated that reconnection persisted at an extended and continuous X-line within the heliospheric current sheet, HCS, for at least 5 hours [*Gosling et al.*, 2007a].

[4] Estimates of reconnection persistence and spatial extent to date have been limited by the spatial extents and orientations of current sheets present in the solar wind and by available spacecraft separations. The recent launch of the twin STEREO A and B spacecraft into orbits about the Sun that increasingly lead (A) and lag (B) the Earth has opened up an opportunity to extend these estimates to greater distances and longer times as the spacecraft drift ever farther from one another and from the Sun-Earth line. Here we report plasma and magnetic field observations on 11 March 2007 by STEREO A and B, Wind, Geotail, and the Advanced Composition Explorer (ACE) of the oppositely directed exhaust jets from a reconnection X-line in the solar wind that extended at least $4.26 \times 10^6$ km ($5.4 \times 10^4$ ion inertial lengths) and where reconnection must have persisted for at least 5 hours and 20 minutes.

## 2. Observations and Analysis

[5] STEREO A and B were launched on 25 October 2006 but remained relatively near Earth for several months before being placed via lunar gravitational assists into solar orbits leading and trailing Earth. By 1 March 2007 both spacecraft were in the solar wind and sufficiently separated from one another (by $6.26 \times 10^6$ km = 982 Earth radii, Re) and from

[1]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, USA.
[2]Institute of Physics, University of Bern, Bern, Switzerland.
[3]Space Sciences Laboratory, University of California, Berkeley, California, USA.
[4]Space Science and Engineering Division, Southwest Research Institute, San Antonio, Texas, USA.
[5]Space Science and Applications, Los Alamos National Laboratory, Los Alamos, New Mexico, USA.
[6]Goddard Space Flight Center, Greenbelt, Maryland, USA.
[7]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.
[8]Physics Department, University of New Hampshire, Durham, New Hampshire, USA.


0094-8276/07/2007GL031492$05.00

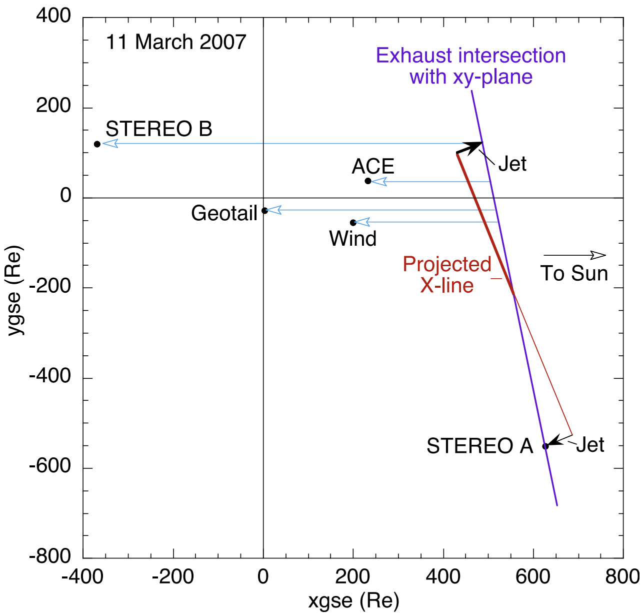


**Figure 1.** GSE x, y coordinates of STEREO A, ACE, Wind, Geotail and STEREO B in the solar wind on 11 March 2007 in Earth radii, Re, (6378 km). The corresponding GSE z-positions of the spacecraft were −33.76, −14.76, −16.77, −6.79, and −25.33 Re, respectively. The violet line indicates the intersection of the 11 March 2007 reconnection exhaust with the xy-plane at the time when STEREO A encountered the exhaust. The red line shows the projection of the reconnection X-line onto the xy-plane at that time, the thick (thin) portion corresponding to that part of the X-line lying above (below) the xy-plane. Black arrows at the opposite ends of the X-line projection indicate projections of those portions of the exhaust jets observed by STEREO A and B, respectively. Blue arrows indicate the motion of the exhaust intersection as the X-line was carried anti-sunward by the nearly radial solar wind flow. The lengths of the blue arrows are proportional to the predicted time lags relative to STEREO A for the exhaust encounters at the other spacecraft.

the Sun-Earth line to provide measurements useful for placing new limits on reconnection persistence and X-line extents in the solar wind. On the other hand, by early March it had also become increasingly difficult to identify current sheets that spanned the spacecraft separation.

[6] Using plasma [*Lin et al.*, 1995] and magnetic field [*Lepping et al.*, 1995] data from the Wind spacecraft at 3-s resolution we identified 124 reconnection exhausts in the solar wind upstream from Earth in the March-April 2007 interval. Many of these exhausts occurred at relatively small field shear angles and were convected past Wind on time scales <100 s; such narrow exhausts would not be resolved by the 60-s cadence of the ion plasma experiment [*Galvin et al.*, 2007] on the STEREO spacecraft, although the magnetic field experiment [*Luhmann et al.*, 2007] on STEREO is easily capable of resolving such exhausts. Focusing on the subset of exhausts that were convected past Wind on time scales >100 s, we found that only two of the exhausts observed by Wind in the March-April 2007 interval occurred at current sheets that spanned the separation between the two STEREO spacecraft. One of these events occurred in the low-speed wind on 11 March 2007 and is the subject of the present study.

[7] STEREO A and B, ACE, Wind and Geotail were all in the solar wind on 11 March 2007 and were located slightly below the GSE xy-plane. Figure 1 shows the positions of these spacecraft on that day projected onto the GSE xy-plane (Earth is located at the origin of the GSE coordinate system). ACE, Wind and Geotail were all relatively close to the Sun-Earth line, whereas STEREO A was well out ahead of and sunward of Earth in its orbit about the Sun and STEREO B was trailing and anti-sunward of Earth. The two STEREO spacecraft were separated by 1215 Re. Much of that separation was in the radial (from the Sun) direction; the separation transverse to the radial direction was 670 Re.

[8] Figure 2 provides ACE plasma [*McComas et al.*, 1998] and magnetic field [*Smith et al.*, 1998] observations

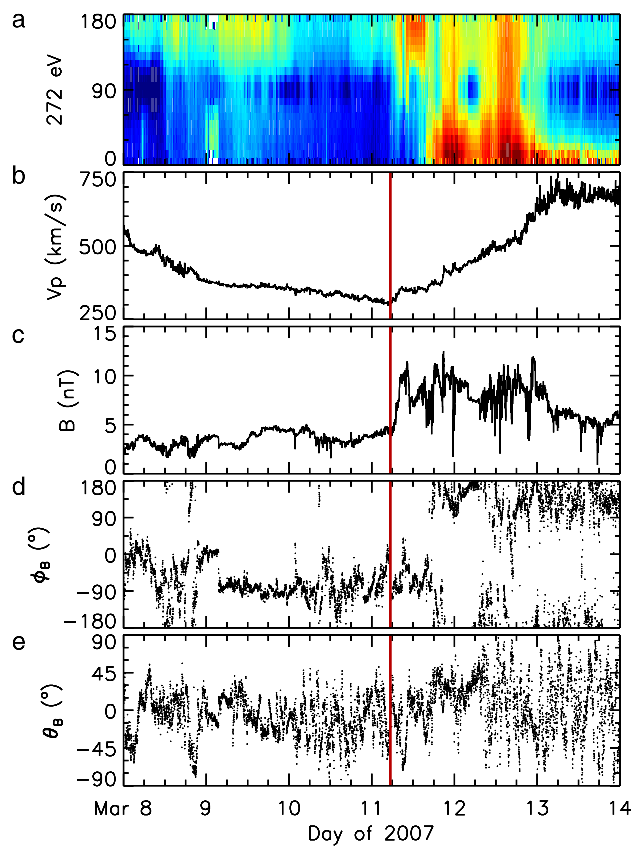


**Figure 2.** Selected solar wind plasma and magnetic field data from ACE for a 6-day interval in March 2007. Parameters shown are (a) the color-coded pitch angle distribution, PAD, of 272 eV suprathermal electrons, (b) solar wind bulk flow speed, (c) magnetic field strength, and (d) field azimuth and (e) latitude angles. The vertical red line indicates the point where ACE encountered the 11 March reconnection exhaust (at 05:23 UT). Color-coding of f(v) in Figure 2a is logarithmic and ranges from $5 \times 10^{-31}$ $s^3$ $cm^{-6}$ (dark blue) to $2 \times 10^{-29}$ $s^3cm^{-6}$ (dark red). The relatively intense beam in Figure 2a that peaked at PA 180° prior to ~1700 UT on 11 March and at 0° thereafter is the solar wind electron strahl. That reversal in the strahl flow polarity, which coincides with a large rotation in the magnetic field, marks a crossing of the heliospheric current sheet.

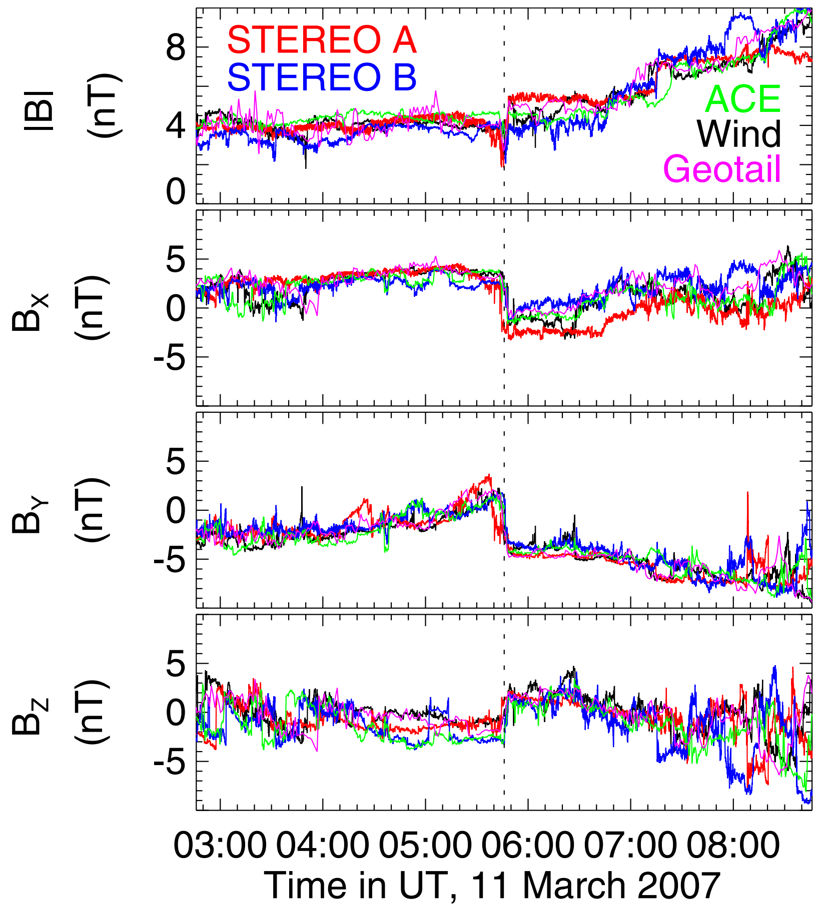


**Figure 3.** A 6-hr overlay of time-shifted magnetic field data from STEREO A, ACE, Wind, Geotail and STEREO B in GSE coordinates on 11 March 2007. The time shifts of +126, +20, 0, −58, and −193 minutes, respectively, were chosen to make the back edge of the bifurcated current sheet (marked by the dotted vertical line) "simultaneous" at the different spacecraft.

of the solar wind environment upstream from Earth in a 6-day interval encompassing the reconnection event, which ACE encountered between 05:23 and 05:28 UT on11 March 2007. The encounter occurred well before (by >11 hours) a crossing of the HCS, at a point where the field rotated ~127° and where the solar wind flow speed was a minimum. The latter indicates that the exhaust was not the result of compression in the solar wind.

[9] Figure 3 demonstrates that STEREO A, ACE, Wind, Geotail, and STEREO B all successively observed the same basic magnetic field structure during a (time-shifted) 6-hr interval on 11 March 2007 roughly centered on the field rotation (encountered by Wind at 05:44 UT and at earlier or later times by the other spacecraft). Despite the overall agreement between the magnetic field observations at the various spacecraft, differences in detail are apparent, including differences in the structure of the field reversal region. However, all five spacecraft observed the reversal as a bifurcated current sheet. Calculated field shear angles for the field reversal at STEREO A, ACE, Wind, Geotail, and STEREO B were 95°, 127°, 133°, 138° and 146°, respectively, indicating the presence of a relatively strong and apparently systematically varying guide field along the current sheet.

[10] The jetting plasma associated with a reconnection exhaust in the solar wind is always bounded by a pair of back-to-back rotational discontinuities at which the changes in flow velocity, ***V***, and magnetic field, ***B***, are correlated on one side and anti-correlated on the other; this provides a clear and unambiguous signature by which to recognize reconnection exhausts in the data [e.g., *Gosling et al.*, 2005a]. Such correlated/anti-correlated signatures in ***V*** and ***B*** were clearly observed at the edges of the field reversal region by the four spacecraft (all except STEREO B) where 3D velocity information was available. However, the jetting plasma at STEREO A was directed in the (−x, −y, +z) GSE direction while that at Wind, ACE and Geotail was directed in the (+x, +y, −z) GSE direction. STEREO B observed a decrease in speed within the field reversal region, consistent with the more complete Wind, ACE and Geotail observations.

[11] Figure 4, which shows a time-shifted overlay of plasma and magnetic field data from STEREO A, Wind and STEREO B in a format similar to that of Figure 3, helps illustrate the above points. In addition, the figure shows that Wind briefly re-entered, but did not fully traverse, the exhaust at 05:51:29 UT. Magnetic field data in Figure 3 indicate that ACE also briefly re-entered the exhaust at approximately the same (shifted) time, although that reentry was not resolved by the 64-s cadence of the ACE plasma measurement. Previous work suggests that incomplete traversals of an exhaust prior to or following a complete

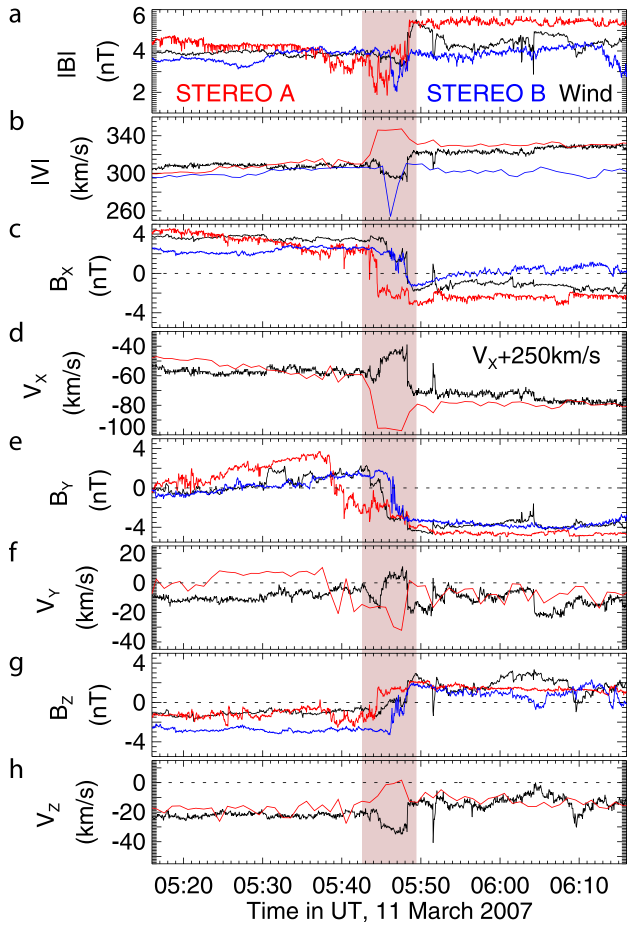


**Figure 4.** A 1-hr overlay of time-shifted plasma and magnetic field data from STEREO A, Wind, and STEREO B in GSE coordinates. No 3D velocity values are available from STEREO B for this time period, but STEREO B did observe a decrease in flow speed (Figure 4b), as did Wind, ACE (not shown), and Geotail (not shown), whereas STEREO A observed an increase in flow speed. Time shifts are as in Figure 3. Shading indicates the reconnection exhaust.

traversal result from local, non-planar aspects, i.e., warping, of the associated exhaust boundaries [*Gosling et al.*, 2007a].

[12] A minimum variance analysis of the magnetic field, MVAB, [*Sonnerup and Cahill*, 1967] data in the vicinity of an exhaust provides a determination of the direction of the normal to the exhaust "plane" and the orientation of the X-line [e.g., *Phan et al.*, 2006]. From a MVAB analysis of the STEREO A data we find that the exhaust normal pointed in the direction (−0.529, −0.110, 0.841) GSE and the X-line was oriented in the direction (−0.377, 0.919, −0.117) GSE. (The MVAB analysis produced a ratio of 12.94 between the intermediate and minimum eigenvalues, so these directions are well-determined.) We note that the X-line was tilted only 6.7° relative to the GSE xy-plane. Figure 1 shows the intersection of the exhaust plane with the xy-plane at the time when STEREO A encountered the (anti-sunward-directed) exhaust and also shows the projection of the X-line onto the xy-plane at that time. STEREO A sampled jetting plasma from a portion of the X-line that lay below the xy-plane, whereas the other 4 spacecraft sampled jetting plasma from portions of the X-line that lay above that plane. (We are ignoring here the slight displacement of all the spacecraft below the GSE xy-plane.)

[13] STEREO A first encountered the anti-sunward-directed exhaust from the 11 March reconnection event at 03:38 UT. ACE, Wind, Geotail and STEREO B subsequently encountered the sunward-directed exhaust 105, 126, 184, and 320 minutes later, respectively. In order for all five spacecraft to have encountered jetting plasma from the X-line, we surmise that reconnection must have persisted for at least 320 minutes along the entire X-line. Using the observed background solar wind speed of ~300 km/s and the orientation of the exhaust intersection with the GSE xy-plane shown in Figure 1, the predicted lag-times (relative to STEREO A) for exhaust arrivals at the other spacecraft are 96, 115, 182 and 309 minutes, respectively, in reasonably good agreement with the observed lags. This indicates that the 11 March 2007 exhaust was roughly planar over a distance of 684 Re or $4.36 \times 10^6$ km (the separation distance between STEREO A and B along the direction of the exhaust intersection line). Owing to the slight (12.4°) tilt of the X-line relative to the intersection of the exhaust with the xy-plane, our estimate of the X-line extent is slightly smaller than the above distance. We find that the X-line extended at least 668 Re, or $4.26 \times 10^6$ km.

## 3. Discussion

[14] Measurements of oppositely directed plasma jets within a bifurcated current sheet by five well-separated spacecraft in the solar wind on 11 March 2007 provide further strong confirmation that such jets result from reconnection and reveal the tremendous length that a reconnection X-line can have within an extended current sheet in a space plasma in the presence of a relatively strong and variable guide field. Our derived lower limit for the X-line extent ($4.26 \times 10^6$ km = 668 Re = 0.0284 AU = 6.12 solar radii) in this event is a factor of 1.7 greater than was derived for the 2 February 2002 event [*Phan et al.*, 2006], whereas our derived lower limit for the reconnection time (320 minutes) is a factor of 1.07 greater than was derived for the 31 August–1 September 2001 event [*Gosling et al.*, 2007a]. Of course, the actual X-line length and reconnection duration for each of these events may have been considerably greater than the lower limits we have been able to obtain from available spacecraft separations.

[15] Measurements of X-line lengths and reconnection durations are important because, along with reconnection rates, those quantities determine how much magnetic flux is reconnected in an event. How, then, do long reconnection times and extended X-lines arise in the solar wind? With regard to the former, both theory and numerical simulation indicate that pressure gradients associated with the rarefaction produced by the outflow of plasma from the diffusion region sustain reconnection by continually accelerating new plasma and magnetic field into the diffusion region [e.g., *Vasyliunas*, 1975]. Indeed, in simulations with uniform plasmas and fields on opposite sides of a thin current sheet, reconnection, once initiated, is difficult to turn off because of such effects (M. Hesse, personal communication, 2006).

[16] With regard to X-line extents, numerical simulations for the case of strictly anti-parallel magnetic fields indicate that ion and electron flows in the diffusion region, driven by the reconnection electric field (which points in the direction of the X-line), cause an initially short X-line to expand at a rate that is a significant fraction of the external Alfvén speed [e.g., *Shay et al.*, 2003; *Lapenta et al.*, 2006]. Assuming expansion at the average external Alfvén speed ($\sim$64 km/s) in the 11 March 2007 event, it would have taken 18.5 hours to produce an X-line that extended $4.26 \times 10^6$ km. Such long reconnection times are not out of the range of what we think is possible in the solar wind. On the other hand, in the presence of a strong guide field X-line expansion might proceed much faster, perhaps at electron thermal speeds (J. Drake and G. Lapenta, personal communication, 2007). Finally, we note that the spherical expansion of the solar wind causes the transverse dimensions of structures like X-lines to grow directly as heliocentric distance and almost certainly also contributes to the production of extended X-lines in the solar wind at 1 AU.

[17] Opportunities for extending limits on X-line extents and persistence in the solar wind should occur as the STEREO spacecraft drift ever farther apart, although we have already found that it is increasingly difficult to identify current sheets that 1) span the separation between STEREO A and B in the March and April 2007 time frame, and 2) contain reconnection exhausts that can be resolved by the ion plasma experiment on STEREO. The best opportunities for identifying extended current sheets may arise during encounters with the heliospheric current sheet or with the leading edges of ICMEs. The HCS is both extensive and, as Figure 2 shows, easily recognized by the simultaneous changes in both magnetic field polarity and suprathermal electron flow polarity that occur there [e.g., *Kahler et al.*, 1998], while the leading edges of ICMEs are also usually extensive and readily identified in the data as well. On the other hand, previous work [e.g., *Gosling et al.*, 2005b] indicates that reconnection occurs relatively infrequently at the HCS and at the leading edges of ICMEs.

[18] **Acknowledgments.** We thank J. Drake, D. Krauss-Varban, G. Lapenta, and M. Hesse for useful discussions and the STEREO project and L. Frank, S. Kokubun, R. Lepping, R. Lin, C. Smith, and the CDAWeb for making available data used in this paper. This work has been supported by NASA grant NNG06GC27G, NAS5-00132, and the NASA STEREO Program.

## 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.

Galvin, A. B., et al. (2007), The plasma and suprathermal ion composition (PLASTIC) investigation on the STEREO observatories, *Space Sci. Rev.*, in press.

Gosling, J. T., R. M. Skoug, D. J. McComas, and C. W. Smith (2005a), Direct evidence for magnetic reconnection in the solar wind near 1 AU, *J. Geophys. Res.*, *110*, A01107, doi:10.1029/2004JA010809.

Gosling, J. T., R. M. Skoug, D. J. McComas, and C. W. Smith (2005b), Magnetic disconnection from the Sun: Observations of a reconnection exhaust in the solar wind at the heliospheric current sheet, *Geophys. Res. Lett.*, *32*, L05105, doi:10.1029/2005GL022406.

Gosling, J. T., S. Eriksson, T. D. Phan, D. E. Larson, R. M. Skoug, and D. J. McComas (2007a), 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., T. D. Phan, R. P. Lin, and A. Szabo (2007b), Prevalence of magnetic reconnection at small field shear angles in the solar wind, *Geophys. Res. Lett.*, *34*, L15110, doi:10.1029/2007GL030706.

Kahler, S., N. U. Crooker, and J. T. Gosling (1998), Properties of interplanetary magnetic sector boundaries based on electron heat-flux flow directions, *J. Geophys. Res.*, *103*, 20,603.

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.

Lepping, R. P., et al. (1995), The Wind magnetic-field investigation, *Space Sci. Rev.*, *71*, 207.

Lin, R. P., et al. (1995), A three-dimensional (3-D) plasma and energetic particle experiment for the Wind spacecraft of the ISTP/GGS mission, *Space Sci. Rev.*, *71*, 125.

Luhmann, J. G., et al. (2007), STEREO IMPACT investigation goals, measurements, and data products overview, *Space Sci. Rev*, in press.

McComas, D. J., et al. (1998), Solar wind electron proton alpha monitor (SWEPAM) for the Advanced Composition Explorer, *Space Sci. Rev.*, *86*, 563.

Petschek, H. E. (1964), Magnetic annihilation, in *AAS-NASA Symposium on the Physics of Solar Flares*, *NASA Spec. Publ.*, *SP-50*, 425.

Phan, T. D., et al. (2006), A magnetic 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.

Smith, C. W., et al. (1998), The ACE magnetic fields experiment, *Space Sci. Rev.*, *86*, 613.

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

Vasyliunas, V. M. (1975), Theoretical models of magnetic field line merging, 1, *Rev. Geophys.*, *13*, 303.

M. H. Acuna, Goddard Space Flight Center, Mail Code 696, Greenbelt, MD 20771, USA.

L. M. Blush, Physikalisches Institut, University of Bern, CH-3012 Bern, Switzerland.

S. Eriksson and J. T. Gosling, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303-7814, USA. (jack.gosling@lasp.colorado.edu)

J. G. Luhmann and T. D. Phan, Space Sciences Laboratory, University of California, Berkeley, Berkeley, CA 94720, USA.

D. J. McComas, Space Science and Engineering Division, Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228-0510, USA.

C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, CA 90095-1567, USA.

K. D. Simunac, Physics Department, University of New Hampshire, Durham, NH 03824, USA.

R. M. Skoug, Space Science and Applications, Los Alamos National Laboratory, MS D466, Los Alamos, NM 87545, USA.