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Direct evidence for prolonged magnetic reconnection at a continuous x-line within the heliospheric current sheet

J. T. Gosling,[1,2] S. Eriksson,[1] T. D. Phan,[3] D. E. Larson,[3] R. M. Skoug,[4] and D. J. McComas[2]

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[1] Observations by 5 spacecraft of an exceptionally broad (1.85×10^6 km) Petschek-type reconnection exhaust within the heliospheric current sheet, HCS, in the solar wind at 1 AU on 31 August and 1 September 2001 provide convincing direct evidence for prolonged (at least 5 hours) magnetic reconnection at a continuous X-line in the solar wind. At least 1.2×10^{24} ergs of magnetic energy were extracted from the HCS in this event and converted to kinetic and thermal energy of the exhaust plasma. The reconnection produced field lines disconnected from the Sun and may have originated inside the point where the solar wind became super-Alfvénic, thereby slightly reducing the amount of open magnetic flux present in the heliosphere. **Citation:** Gosling, J. T., S. Eriksson, T. D. Phan, D. E. Larson, R. M. Skoug, and D. J. McComas (2007), 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.

1. Introduction

[2] It has recently been demonstrated [e.g., *Gosling et al.*, 2005a, 2005b, 2006; *Phan et al.*, 2006; *Davis et al.*, 2006] that magnetic reconnection occurs frequently in the solar wind and produces Petschek-type exhausts, i.e., exhausts of jetting plasma bounded by Alfvén or slow-mode waves [*Petschek*, 1964], emanating from reconnection sites. The exhausts are identified as intervals of roughly Alfvénic accelerated or decelerated flow confined to magnetic field reversal regions that usually take the form of bifurcated current sheets. The exhausts are embedded within the solar wind flow and typically are convected past a spacecraft on time scales ranging from less than a minute to several 10s of minutes, corresponding to local exhaust widths ranging up to $\sim 2 \times 10^6$ km. Reconnection exhausts are observed at thin current sheets in either low-speed wind or in association with coronal mass ejections, CMEs, in plasma predominantly having low proton beta. Only a few events have been identified at the HCS, which separates open field lines of opposite magnetic polarity and which generally wraps entirely around the Sun. Reconnection at the HCS produces closed field lines sunward of a reconnection site [*Gosling et al.*, 2006] and disconnected (from the Sun) field lines anti-sunward [*Gosling et al.*, 2005b].

[3] Multi-spacecraft observations of solar wind reconnection exhausts have provided evidence that the exhausts result from quasi-stationary reconnection at extended reconnection sites (X-lines), in one case persisting for at least 2.5 hours along an X-line that extended for at least 2.5×10^6 km [*Phan et al.*, 2006]. However, in events studied thus far one cannot conclusively rule out the possibility that reconnection was actually patchy in both space and time since each spacecraft typically encountered an exhaust for only a few minutes and sampled only a very limited extent of the X-line. Here we report observations by 5 spacecraft of a broad reconnection exhaust within the HCS where the interpretation of prolonged reconnection along a continuous X-line is unambiguous.

2. Observations and Analysis

[4] Figure 1 provides the GSE locations of SOHO, Wind, ACE, Genesis, and Geotail in the solar wind upstream from Earth at the time of interest to this paper. The spacecraft were well separated in the X-Y plane, but only Genesis was positioned substantially out of that plane. The experiment packages on all 5 spacecraft included plasma instrumentation; those on Wind, ACE and Geotail also included a magnetometer. Figure 2 shows the solar wind speed and magnetic field strength measured by these 5 spacecraft in a 7-hr interval on 31 August and 1 September 2001. The event of interest here is the $\sim$3-hr-long accelerated flow event detected first at SOHO at $\sim$23:24 UT 31 August and then successively at Wind at 23:59 UT, and at Genesis, ACE and Geotail at 00:41, 00:45, and 01:23 UT, respectively, on 1 September. SOHO and Wind, both at relatively large +Y separations from the Sun-Earth line, observed uninterrupted speed enhancements, whereas Genesis, ACE, and Geotail, all in the vicinity of the Sun-Earth line, observed speed enhancements that were interrupted by intervals of varying duration wherein the speed (and field strength) returned to pre-existing solar wind levels.

[5] Figure 3 provides detailed flow velocity and magnetic field vector information for Wind, ACE, and Geotail plotted in a set of exhaust-oriented coordinate (L, M, N) systems determined by minimum variance analyses of the magnetic field, MVAB, [*Sonnerup and Cahill*, 1967; *Phan et al.*, 2006] data in the vicinity of the exhaust at each spacecraft. The MVAB exhaust normals, N, at Wind, ACE and Geotail in GSE coordinates were respectively (0.39, 0.53, −0.75), (0.33, 0.62, −0.72), and (0.36, 0.61, −0.70) and thus differed from one another by less than 6.7°. The calculated maximum, L, and intermediate, M, variance directions were

[1]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, USA.
[2]Southwest Research Institute, San Antonio, Texas, USA.
[3]Space Sciences Laboratory, University of California, Berkeley, California, USA.
[4]Los Alamos National Laboratory, Los Alamos, New Mexico, USA.

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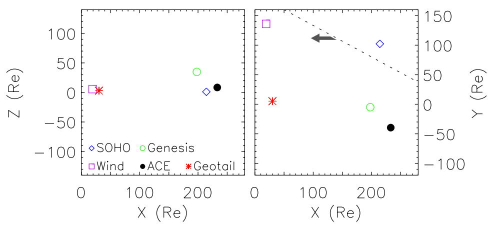

Figure 1. GSE locations of SOHO, Wind, Genesis, ACE, and Geotail in Earth radii, Re, (6378 km) when each spacecraft first detected the reconnection exhaust described in the text. The dashed line in the right panel indicates the intersection of the "plane" of the exhaust, determined from minimum variance analysis of the ACE magnetic field data, with the X-Y plane shortly after passing over SOHO. The arrow indicates the direction of solar wind flow.

also similar at the 3 spacecraft; at Wind those directions were (−0.78, 0.62, 0.03) and (0.48, 0.58, 0.66) respectively. The L-direction for Wind was thus inclined to the GSE X-Y plane by <2°.

[6] Figure 3 shows that: (1) the accelerated flow event at Wind, ACE, and Geotail was associated with a large (∼160°) rotation in the magnetic field, ***B***, with relatively sharp rotations occurring at the event edges and with intermediate and varying field orientations in between; (2) the brief intervals of accelerated flow at ACE centered at ∼00:53 and ∼01:14 UT and at Geotail at ∼01:31 and ∼02:00 UT were associated with incomplete field reversals, with the field returning to its initial orientation at the end of each brief accelerated flow interval; (3) the complete ∼160° field reversals at all spacecraft were accompanied by ∼60 km/s increases in the L-component of the flow velocity, V_L; and (4) changes in V_L, and B_L were correlated at event onset at all 3 spacecraft and were anti-correlated at event end. The latter indicate that the accelerated flow event was bounded by Alfven waves propagating away from the Sun in opposite directions along ***B*** and is the characteristic signature by which we identify reconnection exhausts in the solar wind [e.g., *Gosling et al.*, 2005a].

[7] Figure 4 shows selected plasma and magnetic field data from Wind and demonstrates that: (1) the reconnection exhaust was associated with a crossing of the HCS; (2) transitions from outside to inside the exhaust on both sides were associated with substantial increases in proton number density and proton temperature, decreases in total electron temperature and field strength, and a nearly constant core electron temperature, i.e., the transitions from outside to inside the exhaust were slow-mode-like for the protons but not for the electrons, as is characteristic of most solar wind reconnection exhausts; and (3) except for brief intervals, the electron strahl disappeared within the exhaust. It was the reappearance of a relatively weak strahl shortly before 03:05 UT at PA 0° that establishes that as the time of Wind's exit from the exhaust. Finally, the external proton beta (not shown) was low (0.1–0.2) on both sides of the exhaust, and the external Alfvén speed (not shown) was ∼65 km/s on one side and ∼80 km/s on the other side. Thus this event occurred within low proton beta plasma and the change in V_L (∼60 km/s) from outside to inside the exhaust was comparable to, but slightly less than, the external Alfvén speed.

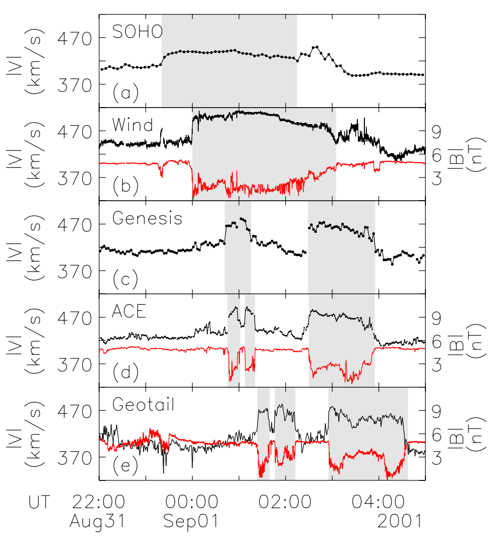

Figure 2. Solar wind speed and magnetic field strength (red lines) as a function of time in the 22:00 UT August 31 – 05:00 UT September 1, 2001 interval as measured at 5 spacecraft. Differences in the speeds measured by the different spacecraft are thought to be associated primarily with differences in instrument calibration. Shading indicates intervals of accelerated flow and associated field strength decreases.

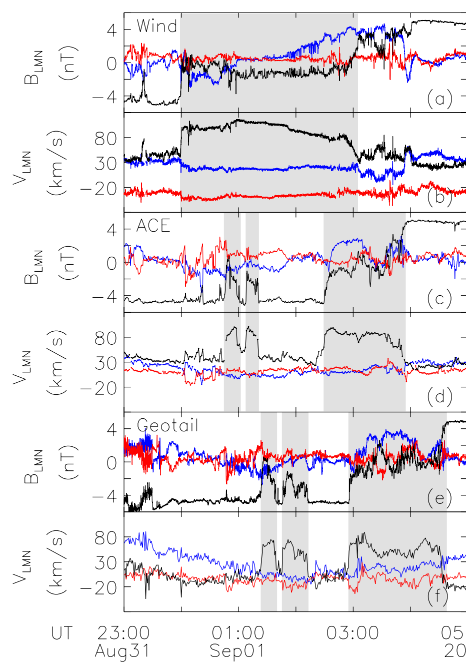

Figure 3. Magnetic field, ***B***, and flow velocity, ***V***, components at Wind, ACE, and Geotail shown in coordinate (L, M, N) systems derived from separate MVAB analyses of the magnetic field data at each spacecraft. Black, blue, and red traces correspond respectively to the L, M, and N components. V_L, V_M and V_N have been shifted by −300, +250 and +150 km/s, respectively, for all three spacecraft. Shading indicates the exhausts.

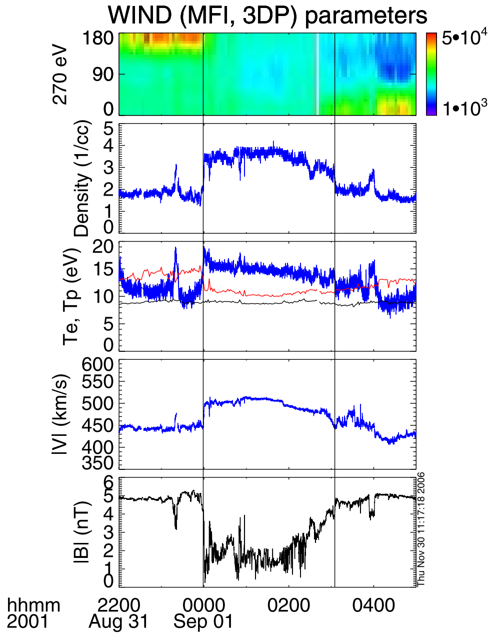

Figure 4. Selected data from Wind on 31 August and 1 September 2001. Parameters shown from top to bottom are the color-coded flux pitch angle distribution, PAD, of suprathermal (270 eV) electrons in the solar wind frame, proton number density, proton (blue) and electron core (black) and total (red) temperatures, flow speed, and magnetic field strength. Vertical lines mark the boundaries of the reconnection exhaust. In the top panel, the relatively intense beam at PA 180° prior to 23:59 UT 31 August and at PA 0° after 03:05 UT 1 September is the "strahl", which carries the solar wind electron heat flux away from the Sun. The reversal of the strahl flow polarity from anti-parallel to parallel to ***B*** near the exhaust edges indicates that the field reversal was associated with a crossing of the HCS.

[8] Changes in plasma and magnetic field properties similar to those shown in Figure 4 were observed during exhaust intervals at the other 4 spacecraft wherever a measurement capability similar to that of Wind was available. This confirms that all 5 spacecraft encountered the same extended HCS-associated reconnection exhaust.

[9] Figure 5 demonstrates that the suprathermal electron PA distributions, PADs, from ACE were anisotropic within the exhaust, the PADs between 0° and 90° being essentially identical to that at those PAs before the exhaust encounter and the PADs between 90° and 180° being essentially identical to that at those PAs after the encounter. This, together with the absence of the strahl within the exhaust, is clear indication that the suprathermal electron PADs within the exhaust resulted from interpenetration along ***B*** of sunward-streaming suprathermal electrons from opposite sides of the exhaust, i.e., there was magnetic connection across the exhaust and field lines there were disconnected from the Sun (see figures and discussion in the work of *Gosling et al.* [2005b]). Although not explicitly shown here, plots of the ACE suprathermal electron PADs at higher temporal resolution reveal a brief interval of weak strahl at PA 180° some minutes after initial entry into the exhaust and also at PA 0° several minutes before final exit from the exhaust, as at Wind. We suspect those brief weak strahl appearances within but near the edges of the exhaust are related to time-of-flight effects associated with strahl electrons draining off disconnected field lines.

[10] One can use the local exhaust normal(s) determined from the MVAB analysis and the measured solar wind velocity outside the exhaust to predict the arrival time of the exhaust at the different spacecraft by assuming that its boundaries were planar surfaces. The dashed line in the right panel of Figure 1 shows the intersection of the exhaust "plane", determined from the MVAB analysis at ACE, with the GSE X-Y plane. Since the solar wind flows nearly in the −X direction it is obvious that the orientation of the intersection of the exhaust with the X-Y plane provides an explanation of the sequential timing of the exhaust arrival at the different spacecraft (see Figure 2). However, using the observed solar wind flow velocity and the MVAB normal(s) the predicted timing delays are substantially (up to 54%) smaller than was actually observed. From this we infer that the leading exhaust boundary was not a simple planar surface. Indeed, we find there is no unique combination of normal direction and flow velocity that quantitatively fits all the observations.

[11] Figure 6 shows the spacecraft trajectories across the exhaust in L, M, N coordinates, thereby revealing its considerable spatial extent. The combined measurements reveal that near 1 AU the exhaust width was at least 290 Re (1.85×10^6 km) and the exhaust extended at least 531 Re (3.4×10^6 km) in the direction of the X-line. We infer from the uninterrupted nature of the SOHO and Wind encounters with the exhaust, from the different coordinates of the temporary ACE, Genesis, and Geotail exits from the exhaust, and from the similarity of the speed profiles at those latter 3 spacecraft, that those exits resulted from the oblique nature of the spacecraft encounters with a non-planar exhaust boundary rather than from temporary cessations of the reconnection process. Indeed, the combined data indicate that reconnection persisted at a continuous extended X-line for at least 4 hr and 58 minutes.

3. Discussion

[12] The multi-spacecraft observations on 31 August–1 September 2001 provide direct evidence for prolonged (~5 hours) reconnection at a continuous X-line within the HCS. In contrast to the 2 February 2002 event studied by

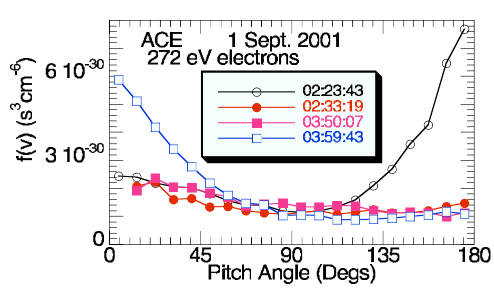

Figure 5. Selected, representative suprathermal electron (272 eV) PAD plots from ACE prior to, during and following ACE's complete traversal across the reconnection exhaust. Similar PADs were obtained at all suprathermal energies.

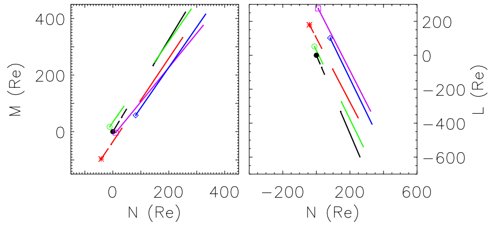

Figure 6. Spacecraft trajectories across the 31 August–1 September 2001 exhaust as measured in L, M, N coordinates determined from MVAB analysis. These trajectories were obtained by decomposing the upstream solar wind velocity into its L, M, N components and using the exhaust crossing times at the respective spacecraft to calculate distances. The N, M, and L-directions are respectively those of the exhaust normal, the reconnection X-line, and the jetting exhaust plasma. Colors for the different spacecraft are as in Figure 1; symbols indicate the starting point for the trajectories relative to the position of ACE, located at L = M = N = 0. Breaks in the ACE, Genesis, and Geotail trajectories correspond to temporary exits of those spacecraft from the reconnection exhaust.

Phan et al. [2006], in which three spacecraft briefly sampled limited and widely separated portions of an extended X-line, in the present case two of the spacecraft (SOHO and Wind) remained in the exhaust for $\sim$3 hours and traversed a distance of $\sim 2.4 \times 10^6$ km along the direction of the X-line during that time. These observations thus provide the most conclusive evidence obtained to date for prolonged reconnection along a continuous X-line in the solar wind.

[13] The exhaust width of 1.85×10^6 km (1.14×10^4 ion inertial lengths, c/ω_{pi}) at 1 AU was near the upper limit of exhaust widths identified thus far in the solar wind at any heliocentric distance. If we assume a uniform solar wind, a dimensionless reconnection rate of .033 [*Phan et al.*, 2006; *Davis et al.*, 2006], and thus an exhaust wedge angle of 3.8°, and that the exhaust jet propagated through the HCS at the local (1 AU) Alfvén speed of $\sim$65 km/s, we find that the jet had propagated for $\sim$5 days and at the time of observation was 2.8×10^7 km (0.19 AU) away from the reconnection site. In the interim, the solar wind flow of $\sim$425 km/s had carried the X-line 1.8×10^8 km (1.2 AU) away from the Sun. Different assumptions lead to different estimates and these are thus subject to considerable uncertainty, particularly since the solar wind is a spherically expanding, rather than a uniform, medium. Nevertheless, these estimates do suggest that the exhaust, which was associated with magnetic field lines disconnected from the Sun, may have originated relatively close to the Sun. Thus the minimum length of the X-line was almost certainly considerably less than the 3.4×10^6 km distance sampled along the direction of the X-line by the 5 spacecraft at 1 AU since a) linear dimensions transverse to the radial direction increase directly as heliocentric distance in the expanding solar wind; and b) we have no way of knowing if reconnection was ongoing when the exhaust jet was sampled at 1 AU. If reconnection occurred sunward of the point where the solar wind became super-Alfvénic, then the reconnection would have produced inflows in the corona [e.g., *Wang and Sheeley*, 2002] and reduced by at least 2 parts in 10^5, and probably considerably more, the amount of open solar magnetic flux in the heliosphere [e.g., *McComas et al.*, 1989].

[14] Reconnection and its aftermath convert magnetic energy to plasma kinetic and thermal energy in the exhaust jets, with almost all of the energy transfer occurring at the extensive exhaust boundaries. With an observed energy gain of about 4.4×10^{-11} erg/ion in the exhaust, we estimate that at least 1.2×10^{24} ergs of magnetic energy, and probably considerably more, was extracted from the HCS in the 31 August–1 September 2001 event. For comparison, the energy dissipated in a major geomagnetic storm is estimated to be $\sim 10^{24}$ ergs [*Baker et al.*, 1997] whereas the energy released in a large flare or CME is $\sim 10^{32}$ ergs.

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S. Eriksson and J. T. Gosling, Laboratory for Atmospheric and Space Physics, University of Colorado, 1234 Innovation Drive, Boulder, CO 80303-7814, USA. (jack.gosling@lasp.colorado.edu)

D. E. Larson and T. D. Phan, Space Sciences Laboratory, University of California, 7 Gauss Way, Berkeley, CA 94720, USA.

D. J. McComas, Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228-0510, USA.

R. M. Skoug, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA.