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Magnetic reconnection in the heliosphere: new insights from observations in the solar wind

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Abstract. Magnetic reconnection plays a central role in the interpretation of a wide variety of observed solar, space, astrophysical, and laboratory plasma phenomena. The relatively recent discovery that reconnection is common at thin current sheets in the solar wind opens up a new laboratory for studying this fundamental plasma process and its after-effects. Here we provide a brief overview of some of the new insights on reconnection derived from observations of reconnection exhaust jets in the solar wind.

Keywords. Magnetic reconnection, solar wind, exhaust jets, plasmas, magnetic fields

1. Introduction

Magnetic reconnection is a physical process that changes magnetic field topology and ultimately converts magnetic field energy to bulk flow energy and plasma heating. It occurs at thin current sheets when the frozen-in field condition of magnetohydrodynamics (MHD) is violated. Original ideas about reconnection had their roots in attempts to explain the sudden release of magnetic energy in solar flares in terms of magnetic neutral points in the solar atmosphere (Giovanelli 1946); however, the concept of reconnection found its first real success in describing the essence of the interaction between the geomagnetic field and the heliospheric magnetic field (HMF) embedded in the solar wind flow (Dungey 1961).

Indirect magnetospheric evidence for reconnection can be found in 1) the association of geomagnetic storms, substorms and erosion of the dayside magnetosphere with southward turnings of the HMF, 2) the sense of magnetospheric convection (generally anti-sunward over the polar caps and sunward at lower latitudes), 3) asymmetric polar cap convection and its dependence on the transverse in-ecliptic component of the HMF, 4) the fact that the polar caps and magnetotail lobes are almost always open to the heliosphere, 5) the hemispheric dependence of polar rain (energetically soft electron precipitation into the polar caps with intensity and spectra comparable to that of the external solar wind electron strahl) on the polarity (toward or away from the Sun) of the HMF, and 6) reconfigurations of the geomagnetic tail in association with geomagnetic activity. Although the above are collectively convincing evidence for reconnection, the first direct evidence came from *in situ* observations of accelerated plasma flows at Earth's magnetopause that were quantitatively consistent with models of the reconnection process (Paschmann *et al.* 1979). Subsequent work has now established beyond any reasonable doubt the fundamental role that reconnection plays in the dynamics of Earth's magnetosphere and, by extension, the dynamics of the magnetospheres of other planets.

We have also come full circle in that scientists now commonly invoke reconnection to explain such diverse solar phenomena as flares, coronal mass ejections (CMEs), post-flare/CME loops, coronal jets, blobs, and down flows and the restructuring of the solar atmosphere in general, as well as coronal heating and impulsive solar energetic particle events. In addition, reconnection is commonly used to explain 1) the mixtures of magnetic field topologies (open, closed, disconnected) often observed within CMEs in the solar wind (ICMEs), 2) the formation of flux rope ICMEs, 3) the rough constancy of open magnetic flux in the heliosphere, and 4) comet tail disconnection events. Indeed, reconnection plays a central role in the interpretation of a wide variety of observed solar, space, astrophysical, and laboratory plasma phenomena (e.g., Priest & Forbes 2000).

2. Magnetic reconnection exhausts in the solar wind

There have been suggestions in the years since reconnection was first "discovered" that the process might also occur in the solar wind far from the Sun, for example at the heliospheric current sheet, HCS, that separates magnetic fields of opposite magnetic polarity and that generally wraps around the Sun, at the leading edges of ICMEs, or at current sheets formed by solar wind turbulence. Only recently, however, have we learned how to recognize the unambiguous signature of local, quasi-stationary reconnection in the solar wind far from the Sun in the form of Petschek-like exhausts i.e., plasma jets propagating away from a reconnection site and bounded by back-to-back rotational discontinuities or slow mode waves (Petschek 1964; Gosling *et al.* 2005a).

Figure 1 shows solar wind plasma and magnetic field data encompassing a reconnection exhaust observed at the leading edge of an ICME on 18 February 1999. The exhaust is identified in the data by the roughly Alfvènic accelerated plasma flow (primarily in the n-component) confined to the region where the magnetic field rotated (also primarily in the n-component) and bounded on one side by anticorrelated changes in flow velocity, **V**, and magnetic field, **B**, and by correlated changes in **V** and **B** on the other. This is the characteristic signature by which we identify reconnection exhausts in the solar wind. We note that the field reversal occurred in two distinct, but unequal, steps with the field lingering at an intermediate orientation in between. The total field rotation was about 120° and occurred over an interval of about 3.5 minutes, corresponding to a maximum exhaust width of about 1.3×10^5 km. An increased proton temperature, a decreased magnetic field strength, and a proton density intermediate between the densities on opposite sides also characterized the exhaust, which was embedded within low beta plasma on both sides. Such changes in proton temperature, proton density and field strength are characteristic of many, but certainly not all, reconnection exhausts in the solar wind.

Figure 2 provides a highly idealized planar projection of a slightly asymmetric reconnection exhaust (the oppositely directed exhaust is not shown) convecting with the nearly radial (from the Sun) solar wind flow and a brief explanation of how an exhaust is formed. A large fraction of the field rotation across an exhaust in the solar wind occurs at the two exhaust edges where the plasma entering the exhaust is accelerated. We call these back-to-back rotational discontinuities a bifurcated current sheet since they result from a splitting of a current sheet as an after-effect of the reconnection process.

As illustrated in Figure 3, elevated proton temperatures commonly observed within solar wind reconnection exhausts are associated with interpenetrating (along **B**) proton beams (not always well resolved) rather than with simple broadened thermal distributions. The counterstreaming proton beams enter into an exhaust from opposite sides as a result of the Alfvènic disturbances that propagate in opposite directions along reconnected field lines and that mark the edges of an exhaust. The beams thus have a relative

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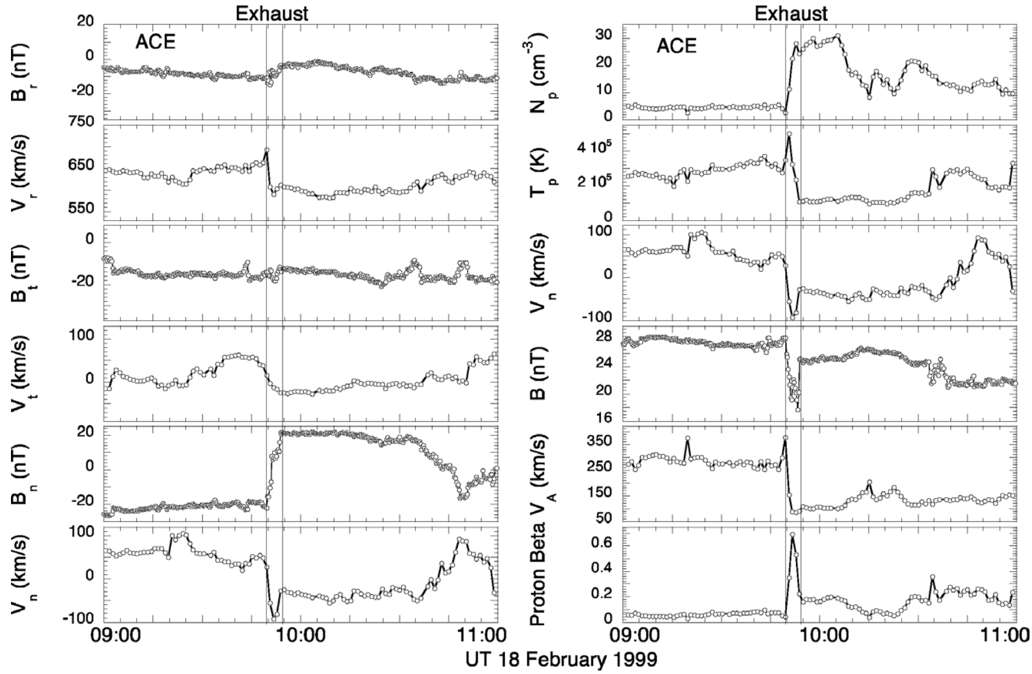

Figure 1. Selected solar wind plasma (at 64-s resolution) and magnetic field (at 16-s resolution) parameters from ACE, then positioned in the solar wind upstream from Earth at (243.2, 0.61, 24.1) R_e in GSE coordinates, surrounding a reconnection exhaust observed on 18 February 1999. The plasma flow velocity and magnetic field components on the left are shown in r, t, n coordinates, where +r is radial out from the Sun, +t points in the direction of solar rotation at constant heliolatitude, and +n completes a right-handed system. Shown from top to bottom on the right are proton number density and temperature, the n-component of the flow velocity, the magnetic field strength, the Alfvèn speed and the proton beta (ratio of gas to field pressure). Vertical lines bracket the reconnection exhaust. The magnetic shear angle across the exhaust was 120°. Adapted from Gosling *et al.* (2007b).

field-aligned speed within an exhaust that is comparable to the sum of the anti-parallel components of the local Alfvèn speeds on opposite sides of a reconnecting current sheet and demonstrate that a magnetic connection exists across an exhaust.

Suprathermal electrons having energies at 1 AU greater than about 70 eV can also be used to demonstrate magnetic connection across an exhaust in reconnection events that occur at the HCS. In the normal solar wind suprathermal electrons are nearly collisionless and can usually be split into two components: 1) a relatively intense focused beam known as the strahl that is directed outward from the Sun along the magnetic field and 2) a roughly isotropic component that we call the halo and that originates largely from scattering out of the strahl beyond 1 AU, the anti-sunward-directed portion of the halo largely resulting from magnetic mirroring of the sunward-directed portion at locations sunward of the observation point. Figure 4a shows the evolution of the suprathermal electron pitch angle distributions, PADs, during a crossing of an antisunward-directed exhaust detected by ACE at the HCS between 03:17:33 and 30:20:29 UT on 17 September 1998. The HCS crossing is identified in Figure 4a by the change in strahl flow polarity, being parallel to **B** (peaking at 0° pitch angle) on one side and antiparallel to **B** (peaking at 180°) on the other. The field was thus directed outward from the Sun prior to the crossing and directed inward afterwards. Notably, however, the strahl disappeared within the exhaust itself where accelerated plasma flow was detected (not shown). There the

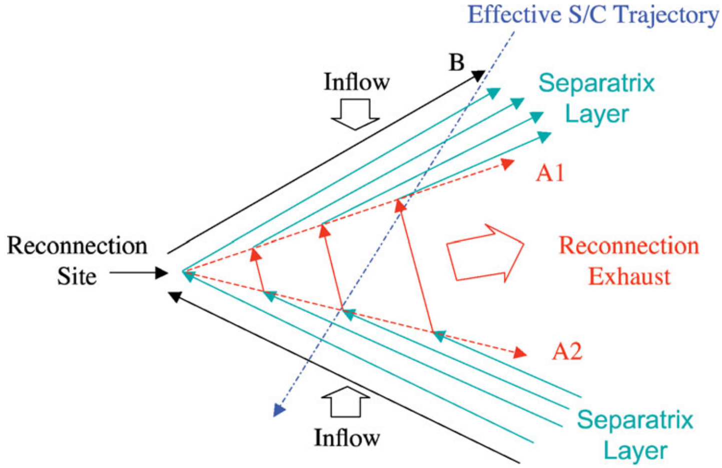

Figure 2. Highly idealized planar projection of a slightly asymmetric reconnection exhaust convecting with the nearly radial (from the Sun) solar wind flow. The sharp field line kink produced by reconnection propagates as a pair of Alfvènic disturbances parallel and antiparallel to a reconnected field line into the plasma on opposite sides of the reconnecting current sheet. As the Alfvènic disturbances propagate they accelerate the plasmas they intercept into the exhaust and away from the reconnection site, thus extracting energy from the reconnecting current sheet. The dashed lines A1 and A2, which pass through the kink pairs on successive reconnected field lines, mark the pair of current sheets (back-to-back rotational discontinuities or slow mode waves) that result from this process and that bound the reconnection exhaust. In practice, the reconnecting fields almost always also have substantial out-of-plane components (parallel to the reconnection X-line). The dash-dot line indicates the projection of an effective spacecraft trajectory through the exhaust. The spacecraft would observe anti-correlated changes in **V** and **B** as it enters the exhaust and correlated change in **V** and **B** as it exits the exhaust since Alfvènic disturbances propagating parallel (antiparallel) to **B** produce anticorrelated (correlated) changes in **V** and **B**, respectively. Adapted from Gosling *et al.* (2005a).

PAD between 0° and 90° was essentially identical to that at those pitch angles after the crossing and the PAD between 90° and 180° was essentially identical to that at those pitch angles prior to the crossing.

As illustrated in Figure 4b, reconnection at the HCS creates closed field lines (connected to the Sun at both ends) sunward of a reconnection site and disconnected (from the Sun) field lines anti-sunward of a reconnection site. In the latter case the evolution of the suprathermal electron PADs from one side of the exhaust to the other should be as illustrated in Figure 4b, exhibiting within the exhaust itself a PAD consisting of suprathermal halo electrons that originally were all sunward-directed on opposite sides of the HCS. The suprathermal electron evolution observed in the 17 September 1998 event (Figure 4a) is consistent with this expectation and thus demonstrates electron interpenetration, magnetic connection across the exhaust, and magnetic disconnection from the Sun. In contrast, one expects to observe closed field lines and counterstreaming strahls within an exhaust sunward of a HCS reconnection site; observations sunward of HCS reconnection sites in other events have confirmed that expectation (Gosling *et al.* 2006).

Multi-spacecraft observations demonstrate that reconnection in the solar wind is commonly a quasi-stationary process that occurs at extended reconnection X-lines (Phan *et al.* 2006; Gosling *et al.* 2007a; Gosling *et al.* 2007d). Estimates of reconnection persistence and spatial extent are limited by the spatial extents and orientations of current sheets present in the solar wind and by available spacecraft separations. The launch of the twin STEREO A and B spacecraft in October 2006 into orbits that increasingly lead

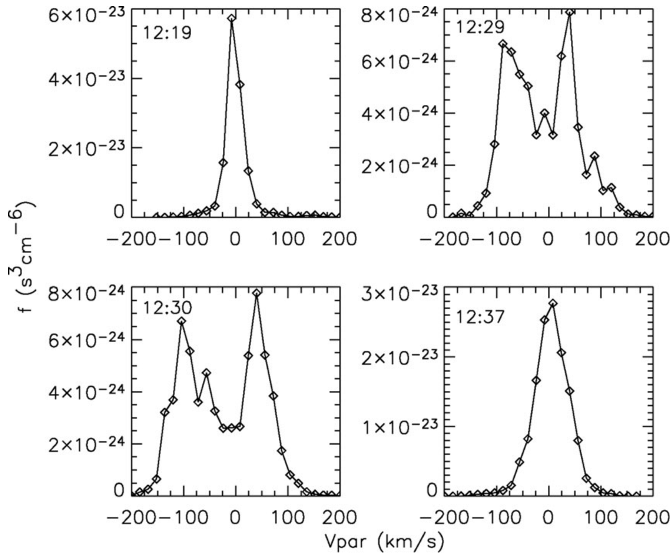

Figure 3. Selected examples of the reduced proton distribution function in the solar wind frame obtained inside (upper right and lower left frames) and outside (upper left and lower right frames) a reconnection exhaust observed on 23 November 1997. Adapted from Gosling *et al.* (2005a).

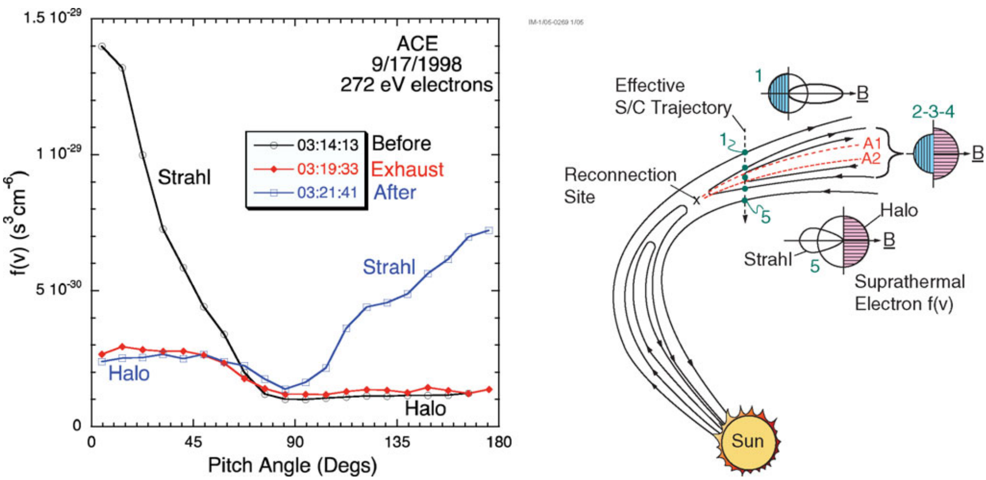

Figure 4. (a) Sequence of 272 eV electron pitch angle distributions in the solar wind frame obtained during a crossing of a reconnection exhaust at the HCS. Adapted from Gosling *et al.* (2005b). (b) Idealized 2-dimensional sketch of reconnection at the HCS illustrating the evolution of the suprathermal electron PADs on the antisunward side of the reconnection site. Adapted from Gosling *et al.* (2005b).

(A) and lag (B) the Earth in its orbit about the Sun opened up a unique opportunity to probe reconnection persistence and the spatial extents of reconnection X-lines in the solar wind.

Figure 5 shows the relative positions of STEREO A and B and 3 other spacecraft (ACE, Wind and Geotail) in the solar wind on 11 March 2007 when all 5 spacecraft observed an extended current sheet. The two STEREO spacecraft were separated by 1215 R_e

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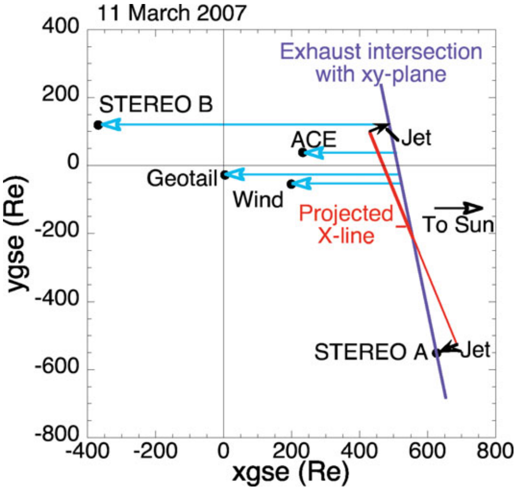

Figure 5. GSE x, y coordinates of STEREO A, ACE, Wind Geotail and STEREO B in the solar wind on 11 March 2007 in Earth radii, Re. All of the spacecraft were nearly in the ecliptic plane. The violet line indicates the intersection of the 11 March 2007 reconnection exhaust with the xy-plane at the time when STEREO A first encountered it. 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 (later) STEREO B, respectively. Blue arrows indicate the motion of the exhaust intersection as the X-line was carried antisunward by the nearly 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. Adapted from Gosling *et al.* (2007d).

(1 $R_e = 6378$ km) at this time, their separation transverse to the radial (from the Sun) direction being 670 R_e. Figure 6 shows a time-shifted overlay of plasma and magnetic field data from STEREO A, Wind and STEREO B surrounding a reconnection exhaust observed by all 5 spacecraft on this day. STEREO A observed an increase in flow speed within the exhaust and correlated (anticorrelated) changes in **V** and **B** at the leading (trailing) edge of the exhaust, whereas the other 4 spacecraft observed a decrease in flow speed within the exhaust and, except for STEREO B where 3D flow measurements were not available, anticorrelated (correlated) changes in **V** and **B** at the leading (trailing) edge. Thus STEREO A observed the antisunward-directed exhaust jet from an extended X-line and the other 4 spacecraft observed the oppositely directed exhaust jet, indicating that the reconnection X-line must have crossed the xy-plane somewhere between STEREO A and Wind, as illustrated in Figure 5 (see also Davis *et al.* 2006).

From a minimum variance analysis of the magnetic field data in the vicinity of the exhaust as observed at STEREO A, we find that the exhaust intersection with the xy-plane and the projection of the X-line onto that plane were as shown in Figure 5, with the X-line being tilted relative to the xy-plane by about 7°. Assuming a planar exhaust boundary and a radial solar wind flow of 310 km/s, the predicted delays for the arrival of the exhaust at ACE, Wind, Geotail, and STERO B, respectively were 96, 115, 182 and 309 minutes, in reasonably good accord with observed delays of 105, 126, 184 and 320 minutes. We find that the X-line extended at least 668 R_e (4.26×10^6 km) and that reconnection must have persisted for at least 320 minutes. This event thus reveals the tremendous length that a reconnection X-line can have within an extended current sheet and demonstrates how persistent reconnection can be in the solar wind.

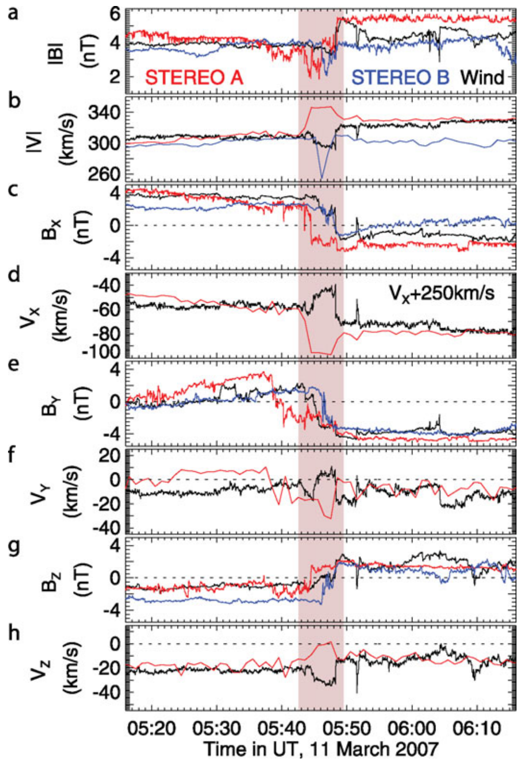

Figure 6. A 1-hr overlay of time-shifted plasma and magnetic field data from STEREO A, Wind, and STEREO B in GSE coordinates. The time shifts for STEREO A and B data relative to the Wind data were +126 and -193 minutes, respectively. Shading indicates a reconnection exhaust observed by all three spacecraft (as well as by ACE and Geotail, not shown). Adapted from Gosling *et al.* (2007d).

Our original examination of 64-s solar wind data from ACE suggested that reconnection occurs only rarely in the solar wind far from the Sun. However, with the development of better techniques for displaying data and by going to higher temporal resolution (3-s) measurements, the situation changed dramatically. We now know that reconnection is relatively common at thin current sheets in the solar wind. Figure 7 provides an overview of solar wind speed and magnetic field variations in March 2006, during the approach to the most recent solar activity minimum. Several high-speed streams of modest amplitude and width were observed during this month; the dominant stream occurred in the March 19-23 interval. Regions of strong magnetic field were present on the leading edges of all the high-speed streams, a result of compression that occurred there. Crossings of the HCS, of which there were at least 4 during the month, can be recognized in Figure 7 as locations where the field azimuthal angle switched from about 135 to about 315° or visa versa. Numerous other current sheets were encountered during March 2006, some of which produced sharp, but often relatively small, changes in the 1-hr averages of the field azimuth and latitude angles. As indicated in Figure 7, we identified at least 46 reconnection exhausts in the Wind 3-s data in this month. All were characterized by correlated changes in **V** and **B** at one edge and by anticorrelated changes in **V** and **B** at the other edge, and thus also by the double-step magnetic field rotations associated with bifurcated current sheets. All but one of the events were observed in relatively low-speed solar wind. A few of the events were observed at times of increasing solar wind speed;

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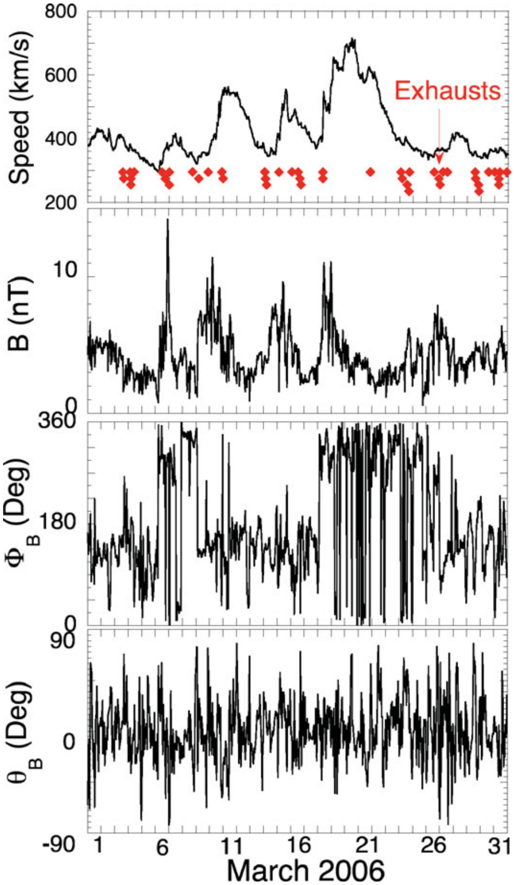

Figure 7. From top to bottom, 1-hr averages of solar wind speed, magnetic field strength, and the azimuth and latitude angles of the heliospheric magnetic field in March 2006. Diamonds placed beneath the speed profile in the top panel indicate times of Wind encounters with reconnection exhausts. Adapted from Gosling *et al.* (2007c).

however, the majority of the events were observed at times of decreasing or nearly constant wind speed, suggesting that reconnection in the solar wind is not typically driven by speed gradients associated with the leading edges of high-speed streams. Although not obvious in the figure, none of the March 2006 exhausts occurred at the HCS and none were associated with ICMEs, since no ICMEs were encountered during the month. Typically, the exhausts were asymmetric; i.e. they occurred at interfaces separating plasmas with somewhat different temperatures, densities, or field strengths. Most of the exhausts occurred in plasma having considerably lower than average plasma beta.

Figure 8 demonstrates that the large majority (89%) of the exhausts observed in March 2006 had local widths less than 4×10^4 km (about 400 ion skin depths), corresponding to exhaust crossing times < about 100 s in a 400 km/s solar wind. Exhausts have been identified down to about the limit of what can be resolved by the Wind 3-s plasma measurement cadence; the narrowest exhaust identified to date in the Wind combined 3-s plasma and magnetic field data had a maximum width of 1×10^3 km (18 ion skin depths). Since that width is still larger than the expected width (about one ion skin depth) of the diffusion region where reconnection actually occurs (Priest & Forbes 2000), there probably are a number of additional exhausts unresolved by 3-s plasma measurements.

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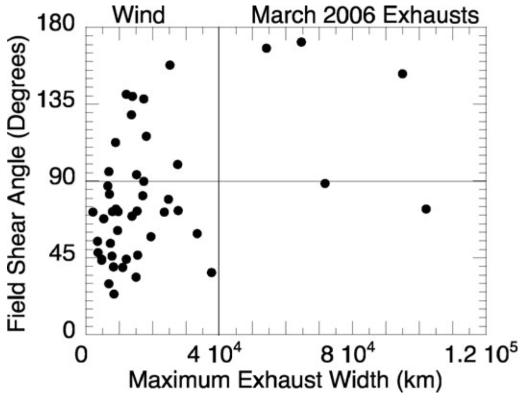

Figure 8. Scatter plot of local magnetic field shear angle versus maximum local exhaust width for the March 2006 reconnection exhausts. Adapted from Gosling *et al.* (2007c).

That expectation is supported by examination of a limited set of current sheets unresolved by a 3-s plasma measurement using 92-ms magnetic field data from Wind that revealed that 10 - 20% of such thin current sheets exhibit the double-step magnetic field rotations characteristic of reconnection exhausts (Gosling & Szabo 2008). In contrast, the broadest exhaust yet identified at 1 AU was 1.85×10^6 km wide and was also characterized by a double-step magnetic field rotation (Gosling *et al.* 2007a).

Perhaps the most remarkable aspect of Figure 8 is that it reveals that the large majority (70%) of the March 2006 exhausts were associated with local field shear angles less than 90°, the smallest field shear angle in this set of events being only 24°. We have recently identified reconnection exhausts associated with local field shear angles as small as 15°. The above clearly indicates that reconnection in the solar wind occurs most often at locations where the so-called guide field component (parallel to the reconnection X-line) considerably exceeds the anti-parallel components. This provides a strong demonstration that, contrary to some perceptions, reconnection does not require or depend on the presence of nearly anti-parallel magnetic fields. The reason for the prevalence of events in the solar wind at current sheets associated with relatively small local field shear angles is simply due to the fact that such current sheets are dominant in the solar wind (see, for example, Figure 7). Further study reveals that our March 2006 results are representative for the solar wind in general near solar activity minimum.

3. Summary

It is now widely appreciated that magnetic reconnection plays a central role in a wide variety of observed solar and space plasma phenomena. The recent recognition that reconnection occurs commonly in the solar wind opens up a new and valuable laboratory for studying the reconnection process and its after-effects. Among other things, work to date has shown that reconnection in the solar wind commonly occurs in a quasi-stationary mode at extended X-lines. It occurs at thin current sheets and produces Petschek-like exhausts of roughly Alfvénic jetting plasma bounded by back-to-back rotational discontinuities that bifurcate the reconnecting current sheets. Reconnection most often occurs in the solar wind in the presence of strong guide fields and low plasma beta. It is quite common in the low-speed wind (40-80 events/month are encountered upstream from Earth) and within ICMEs, but is observed less frequently at current sheets in the Alfvènic turbulence characteristic of the high-speed wind from coronal holes (Gosling 2008). Reconnection in the solar wind often appears to be spontaneous and is usually "fast" but not "explosive" - the magnetic energy release occurs over a long interval following reconnection as the Alfvènic disturbances initiated by reconnection propagate into the surrounding solar wind. Finally, although not explicitly demonstrated here, there is as yet no hard evidence to suggest that reconnection in the solar wind ever produces any substantial particle acceleration (Gosling *et al.* 2005c).

The solar wind results complement and extend our understanding of reconnection as derived from *in situ* measurements at Earth's magnetopause and in the geomagnetic tail. Some questions arising from the observations reported here include:

(*a*) Can reconnection be initiated spontaneously or must it be driven by an external flow?

(*b*) What sustains reconnection and what turns it off?

(*c*) What determines whether reconnection is quasi-stationary or transient?

(*d*) Why does reconnection prefer low plasma beta?

(*e*) How do long reconnection X-lines develop?

(*f*) Are slow mode shocks a necessary aspect of fast reconnection in a collisionless plasma?

(*g*) Does reconnection necessarily produce significant particle acceleration?

(*h*) How important is reconnection in dissipating current sheets in general and in the solar wind in particular?

(*i*) Are essentially all thin current sheets eventually disrupted by reconnection?

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Discussion

Antia: What topological quantum number (like helicity) is changed at magnetic reconnection?

Gosling: My understanding is that helicity is approximately conserved during reconnection. I am not aware of other quantum number effects.

Ibadov: What do you think about disconnections of plasma tails of comets? Some considerations have been made by Prof. J. Brandt.

Gosling: Comet tail disconnections may be associated with reconnections in the manner suggested by Brandt and others, but I do not think that sector boundaries are necessarily the sites of the reconnection. There are many other current sheets in the solar wind that might suffice.

Vlahos: Why do you call the long lived large structures, which can possibly host reconnection, evidence for reconnection?

Gosling: We identify reconnection exhausts as roughly Alfvenic accelerated plasma flows confined to field reversal regions bounded by correlated changes in velocity and magnetic field on one side and by anti-correlated changes in V and B on the other side. Multi-spacecraft observations reveal that such events can be associated with reconnection persisting for hours at a time at very extended X-lines.

Vršnak: Did you check how the inflow/outflow temperature ratio, density ratio, etc depend on the plasma beta and shear angle (and compare that with what is expected from 2.5-Dimensional reconnection models (reconnection in a presence of guiding field).

Gosling: We have not yet compared such predicted and observed temperature and density ratios.

Dasso: You mentioned several observed and inferred signatures of reconnection in the solar wind, such as a Petschek-like structure of the environment of the current sheet and size < 3 times the ion inertial range of protons. Do you think that these signatures are due to the Hall effect of the reconnection?

Gosling: We have not yet identified Hall effect signatures in the solar wind reconnection events studied.