Bifurcated current sheets produced by magnetic reconnection in the solar wind

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Received 11 June 2008; revised 15 July 2008; accepted 30 July 2008; published 17 October 2008.

[1] We report observations from the Wind spacecraft of Petschek-like magnetic reconnection exhausts and thin current sheets in the solar wind on 19 and 20 November 2007, encompassing a solar wind disturbance driven by a magnetic cloud and followed by a corotating high-speed stream. We have identified an unusually large number (11) of reconnection exhausts in this 2-day interval using 3-s plasma and magnetic field data. Despite the relatively smooth large-scale field rotation associated with the magnetic cloud, five of the exhausts occurred within the cloud; three of those exhausts were associated with extremely small (<18°) local field shear angles. All 11 exhausts contained double-step magnetic field rotations; such double-step rotations are called bifurcated current sheets since they result from the splitting of reconnecting current sheets as an after-effect of the reconnection process. We have also identified 27 current sheets in this 2-day interval that were too thin to be adequately resolved by the 3-s plasma measurement cadence. All of these thin current sheets were well resolved by the 92 ms magnetic field measurement. At least three, and possibly six, of these relatively thin current sheets had double-step magnetic field rotations, indicating the underlying current sheets had probably been disrupted by magnetic reconnection. Current sheets thinner than ~3 ion inertial lengths were not present in this data set. The relative lack of such ultrathin current sheets in the solar wind in general suggests that such current sheets usually are quickly disrupted by magnetic reconnection.

Citation: 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.

1. Introduction

[2] It has recently been demonstrated [e.g., *Gosling et al.*, 2005, 2006a, 2006b; *Phan et al.*, 2006] that magnetic reconnection occurs relatively frequently at thin current sheets in the solar wind and produces Petschek-like exhausts [*Petschek*, 1964; *Levy et al.*, 1964], i.e., plasma jets propagating away from a reconnection site and bounded by back-to-back rotational discontinuities or slow mode waves. The exhausts are identified in solar wind data as roughly Alfvénic accelerated or decelerated plasma flows confined to regions where the magnetic field rotates and bounded on one side by correlated changes in velocity, $\boldsymbol{V}$, and magnetic field, $\boldsymbol{B}$, and by anticorrelated changes in $\boldsymbol{V}$ and $\boldsymbol{B}$ on the other. As illustrated in Figure 1, 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 or slow mode waves a bifurcated current sheet since they result from a splitting of a reconnecting current sheet as an after-effect of the reconnection process.

[3] The solar wind contains a rich array of current sheets of varying thicknesses; these are associated with a broad spectrum of field rotation angles, with small rotation angles being dominant [e.g., *Vasquez et al.*, 2007]. Most current sheets observed in the solar wind at 1 AU are not bifurcated and do not contain the accelerated or decelerated plasma flow characteristic of magnetic reconnection. Models of the reconnection process [see, e.g., *Birn et al.*, 2001, and references therein] indicate that reconnection occurs in current sheets having thicknesses comparable to or smaller than an ion inertial length, c/ω_{pi}, which typically is of the order of 50–200 km in the solar wind. Here c is the speed of light and ω_{pi} is the ion plasma frequency. We have identified a very large number of reconnection exhausts having widths $>1.3 \times 10^3$ km ($\sim 13\ c/\omega_{pi}$) in solar wind plasma and magnetic field data obtained at a 3-s cadence on Wind, the highest cadence solar wind plasma measurement currently available. Using 3-s data we have found that Wind encounters, on average, ~2 reconnection exhausts per day in the low-speed wind [*Gosling et al.*, 2007a], and ~0.6 exhausts per day in the high-speed wind [*Gosling*, 2007] that is dominated by Alfvénic-type turbulence. We have not yet obtained similar statistics for interplanetary coronal mass ejections (ICMEs) but preliminary results [e.g., *Gosling et al.*, 2007b], including those from the

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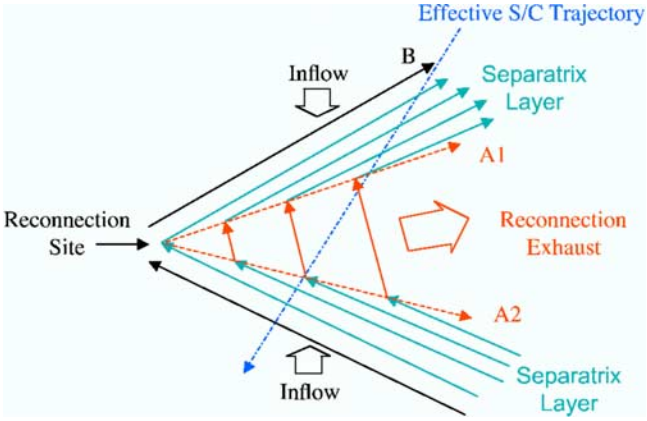

Figure 1. Idealized planar projection of a slightly asymmetric Petschek-like exhaust and separatrix layers on the antisunward side of a reconnection site (X line) and convecting with the nearly radial (from the Sun) solar wind flow. The kink in a magnetic field line produced by reconnection propagates into the plasma on the opposite sides of the original current sheet as a pair of kinks moving parallel and antiparallel to the field line at the respective Alfvén speeds there. As the kink pair propagates, the plasmas the kinks intercept are accelerated into the exhaust and away from the X line, thus extracting energy from the reconnecting current sheet. The red dashed lines A1 and A2, which pass through the kinks on successive reconnected field lines, mark the pair of current sheets (back-to-back rotational discontinuities or slow mode waves) that bound a reconnection exhaust. Note the exhaust width increases with increasing distance from the reconnection site. In practice, the reconnecting fields usually also have substantial out-of-plane components. The blue dash-dot line indicates an effective spacecraft trajectory through the exhaust. (Adapted originally from *Gosling et al.* [2005].)

present paper, indicate that reconnection is common within ICMEs as well. Indeed, a large fraction of the exhausts first identified in the solar wind occurred within ICMEs [*Gosling et al.*, 2005].

[4] The Wind 3-s measurements reveal that reconnection in the solar wind is dominated by events occurring at relatively small (<90°) field shear angles and that most local exhaust widths are $<4 \times 10^4$ km ($\sim 4 \times 10^2$ c/ω_{pi}) at 1 AU [*Gosling et al.*, 2007a]. Since the exhausts are embedded within the solar wind flow, most are convected past a spacecraft in $<\sim 100$ s. A number of exhausts have been identified close to the limit of what can be resolved with a 3-s plasma measurement in the solar wind. For example, an exhaust encountered by Wind at 2017:50 UT on 29 March 2006 was convected past the spacecraft in 3.96 s and had a local width $<1.4 \times 10^3$ km, or ~ 12 c/ω_{pi} [*Gosling et al.*, 2007a]. That width is still large compared to the expected width ($\sim c/\omega_{pi}$) of the current sheet at the reconnection site. We therefore expect that exhausts having local widths smaller than what can currently be resolved by a 3-s measurement should be present in the solar wind, particularly exhausts encountered relatively close to reconnection sites and/or at small field shear angles where reconnection rates are low. Only when such exhausts are routinely resolved will we know how frequently reconnection actually occurs in the solar wind and be able to assess its overall importance in dissipating current sheets and heating and accelerating the solar wind plasma.

[5] As noted above, the double-step nature of the field rotation observed as an exhaust is swept over a spacecraft by the solar wind flow is an almost universal feature of these events (occasionally, however, one or the other of the two steps is not particularly sharp). This suggests that one might identify exhausts that are too thin to be resolved with a 3-s plasma measurement cadence by the double-step magnetic field rotation signature in high-temporal resolution magnetic field data. Before proceeding, however, we note that not all apparent double-step magnetic field rotations in the solar wind that are well resolved by a 3-s plasma measurement (and which thus are broad compared to c/ω_{pi}) contain the accelerated plasma flow characteristic of reconnection exhausts. Such relatively broad, double-step field rotations lacking accelerated plasma may be chance encounters with nearby, but unrelated, current sheets in the solar wind. Alternatively, they may be current sheets that have been bifurcated by processes other than reconnection.

[6] Here we report the results of a study of reconnection exhausts and thin current sheets in the solar wind during a 2-day interval in November 2007 using the onboard-calculated 3-s moments from the 3DP plasma experiment [*Lin et al.*, 1995] and 3-s and 92-ms magnetic field vector data from the magnetic field experiment [*Lepping et al.*, 1995] on the Wind spacecraft. Among other results, we find that the double-step magnetic field rotation signature characteristic of reconnection exhausts was occasionally present in this 2-day interval at current sheets that were too thin to be resolved with a 3-s plasma measurement. This suggests that reconnection is indeed more common in the solar wind than can be revealed by a combined 3-s plasma and magnetic field measurement cadence.

2. Observations

[7] Figure 2 shows a plot of 92-s Wind solar wind plasma and magnetic field data encompassing a disturbance driven by a moderately fast ICME/magnetic cloud and a trailing corotating high-speed stream on 19 and 20 November 2007. This solar wind disturbance produced a small geomagnetic storm (DST minimum of −71 nT at ∼2000 UT on 20 November), the only significant DST disturbance during that month. The ICME/cloud, whose leading and trailing boundaries were marked by rotations in $\boldsymbol{B}$ at 2332 UT on 19 November and at 1146 UT on 20 November, respectively, was identified [see, e.g., *Gosling*, 1990; *Zurbuchen and Richardson*, 2006] in the magnetic field and plasma data by the fact that it was driving a shock into the ambient wind ahead, by the strong and relatively smoothly rotating $\boldsymbol{B}$ throughout the structure, by the anomalously low (for the observed flow speed) proton temperature and hence also low proton beta, and by brief intervals of counterstreaming electrons (not shown in Figure 2), indicating closed field lines in a portion of the structure.

[8] It is not obvious what solar disturbance produced this ICME. It may have been related to an interplanetary disturbance observed by the H1 imager on STEREO-A on 18 November that was estimated to have left the Sun at 0604 on 17 November with an approximate speed of

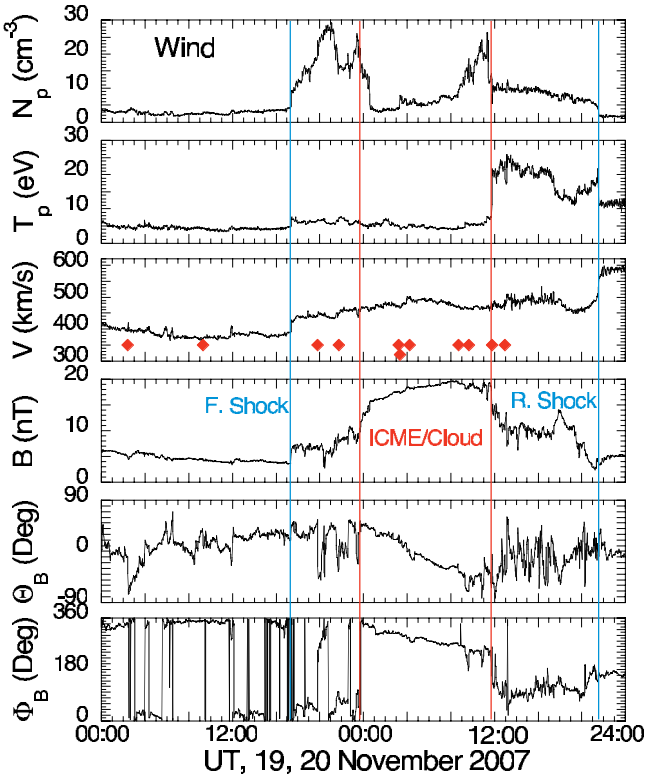

Figure 2. From top to bottom, solar wind proton density, proton temperature, flow speed, and magnitude and azimuth and latitude angles of the heliospheric magnetic field on 19 and 20 November 2007, obtained from the Wind 92-s key parameter data set available on the CDAWeb. During the interval shown Wind was positioned well upstream from Earth, moving from GSE (234.72, 87.87, 15.05) R_E to GSE (236.73, 84.30, 16.25) R_E, where R_E is an Earth radius (6378 km). Vertical blue lines mark shocks and vertical red lines mark the boundaries of an ICME/magnetic cloud. Red diamonds beneath the speed plot indicate times of reconnection exhausts resolved in 3-s data.

600 km/s and predicted arrival at 1 AU at 2027 UT on 19 November. However, the leading edge of the ICME must have been slowed en route from the Sun as a result of its interaction with the slower wind ahead. That interaction produced a relatively high density in the ambient wind between the shock and the ICME as well as in the leading portion of the ICME itself. In turn, the interaction of the trailing, corotating high-speed stream with the rear portion of the ICME produced a compression and acceleration of the ICME there and a reverse shock running back into the high-speed stream.

[9] An almost identical solar wind disturbance was observed at ACE, then separated from Wind by $\sim 8 \times 10^5$ km (largely in the GSE y direction), during this same time interval. The forward shock, ICME, and corotating high-speed stream were also observed by STEREO-B, approximately 20° behind the Earth in its orbit about the Sun. STEREO-A, approximately 20° ahead of the Earth, observed only the corotating stream. The multispacecraft observations of this disturbance are the subject of a separate study. Here the focus is on the reconnection exhausts observed in this 2-day interval and on current sheets not adequately resolved in the Wind 3-s plasma data but well resolved in the Wind 92-ms magnetic field data.

[10] Red diamonds beneath the speed plot in Figure 2 mark the times of 11 reconnection exhausts identified in the 3-s plasma and magnetic field data. That is a particularly large number of reconnection events for a 2-day interval. Only the exhaust at 0225 UT on 19 November produced a speed change that is obvious in the third panel of Figure 2. The plasma acceleration or deceleration produced by reconnection in the other events is not obvious in the 92-s data shown in Figure 2 for a variety of reasons, including the orientations of the reconnection X lines and exhausts, the magnitudes of the velocity changes associated with the exhaust encounters, and/or the widths of the exhausts. Numerous other field rotations (current sheets) occurred in this 2-day interval, most of which were relatively small rotations and not all of which are obvious in the 92-s data shown in Figure 2.

[11] Figure 3 shows vector velocity and magnetic field measurements for a 2-min interval encompassing the second exhaust identified within the ICME/cloud. This relatively thin exhaust was swept past Wind by the solar wind flow in 9.38 s and thus had a maximum local width of 4.4×10^3 km. The total field rotation across this exhaust was only 15°, making this the smallest local field

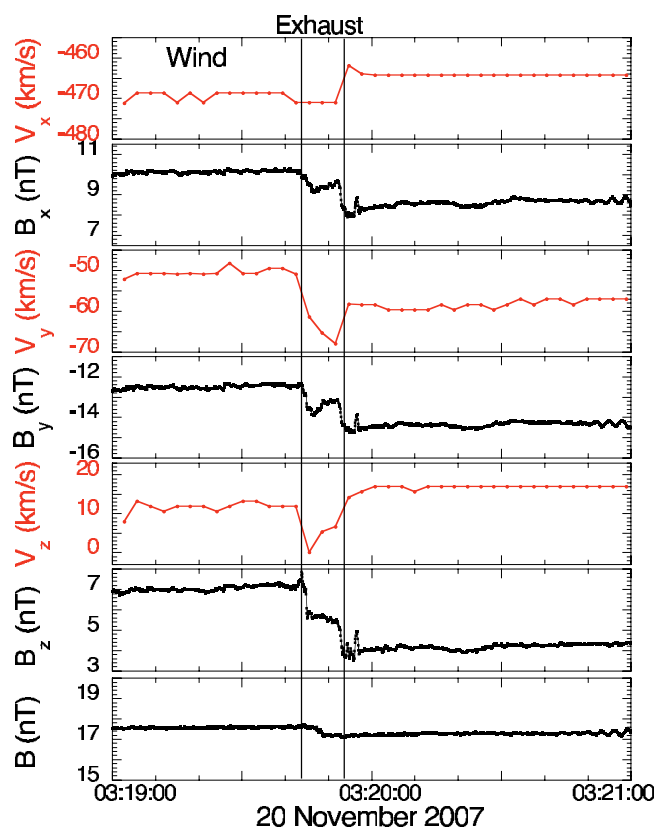

Figure 3. Solar wind velocity (at 3-s resolution) and magnetic field (at 92-ms resolution) data from Wind in GSE coordinates for a 2-min interval on 20 November 2007 within the ICME/cloud. Vertical lines bracket a reconnection exhaust associated with a relatively small (15°) magnetic field rotation.

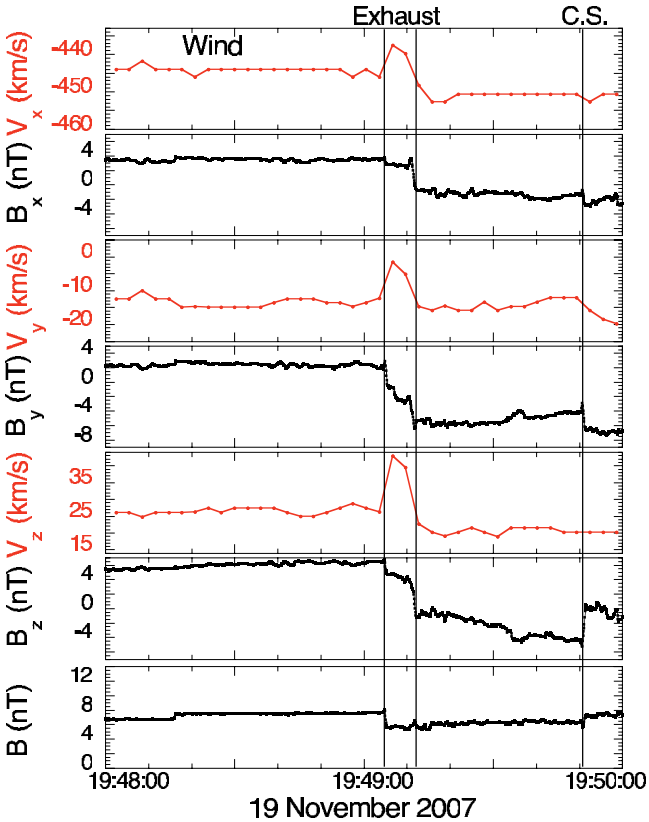

Figure 4. Solar wind velocity (at 3-s resolution) and magnetic field (at 92-ms resolution) data from Wind in GSE coordinates for a 2-min interval on 19 November 2007 within the compressed sheath ahead of the ICME/cloud. Vertical lines near the center of the figure bracket a reconnection exhaust associated with a relatively large (114°) magnetic field rotation, whereas a single vertical line near the right edge marks a relatively simple thin (maximum width 3.3×10^2 km) current sheet associated with a field rotation of 63°.

shear angle yet identified for a reconnection exhaust in the solar wind. The double-step nature of the magnetic field rotation was obvious in the 92 ms data and, as previously noted, is characteristic of reconnection exhausts identified in the solar wind. Changes in $\boldsymbol{V}$ and $\boldsymbol{B}$ were correlated on the leading edge of the exhaust and anticorrelated on the trailing edge. Those coupled changes identify the Alfvénic disturbances that respectively propagated antiparallel and parallel to $\boldsymbol{B}$ on reconnected field lines and that bifurcated the original current sheet. The ratio of the observed average $|\Delta \boldsymbol{V}|$ from outside to inside the exhaust to that predicted by the so-called Walen test [e.g., *Sonnerup et al.*, 1981] was 0.41. As is characteristic of many exhausts observed at small field shear angles in the solar wind, $|\boldsymbol{B}|$ was not depressed within this exhaust, an indication that the exhaust boundaries were not slow mode shocks.

[12] Figure 4 presents similar vector velocity and magnetic field measurements for a 2-min interval encompassing both a reconnection exhaust as well as a simple, single-step current sheet identified within the compressed ambient plasma ahead of the ICME/cloud. The relatively thin (maximum local width 3.3×10^3 km) exhaust was associated with a relatively large (114°) field rotation and exhibited the same basic characteristics as the previous example, except in this case changes in $\boldsymbol{V}$ and $\boldsymbol{B}$ were anticorrelated on the leading edge of the exhaust and were correlated on the trailing edge. The ratio of the observed average $|\Delta \boldsymbol{V}|$ from outside to inside the exhaust to that predicted by the Walen test in this case was 0.87. $|\boldsymbol{B}|$ within the exhaust was essentially the same as that trailing the exhaust, an indication that at least the trailing edge of the exhaust was not a slow mode shock. Notably, the field rotation associated with the exhaust occurred primarily in two distinct steps. In contrast, the 63° magnetic field rotation at 1949:50 UT occurred in a single step lasting 0.74 s, corresponding to a maximum current sheet width of 3.3×10^2 km ($\sim 7\ c/\omega_{pi}$). This thin current sheet was not resolved by the 3-s plasma measurement, but was easily resolved by the 92-ms magnetic field measurement. The lack of a double-step magnetic field signature indicates that it is extremely unlikely that a comparably fast plasma measurement would have revealed a reconnection exhaust within this current sheet. Similarly, Figure 5 shows a 9° field rotation at 0312:18 UT on 20 November that was easily resolved by the 92-ms magnetic field measurement but that was not resolved by the 3-s plasma measurement. This thin (maximum thickness 4.8×10^2 km or 4 c/ω_{pi}) current sheet was swept past the spacecraft in 1.02 s and

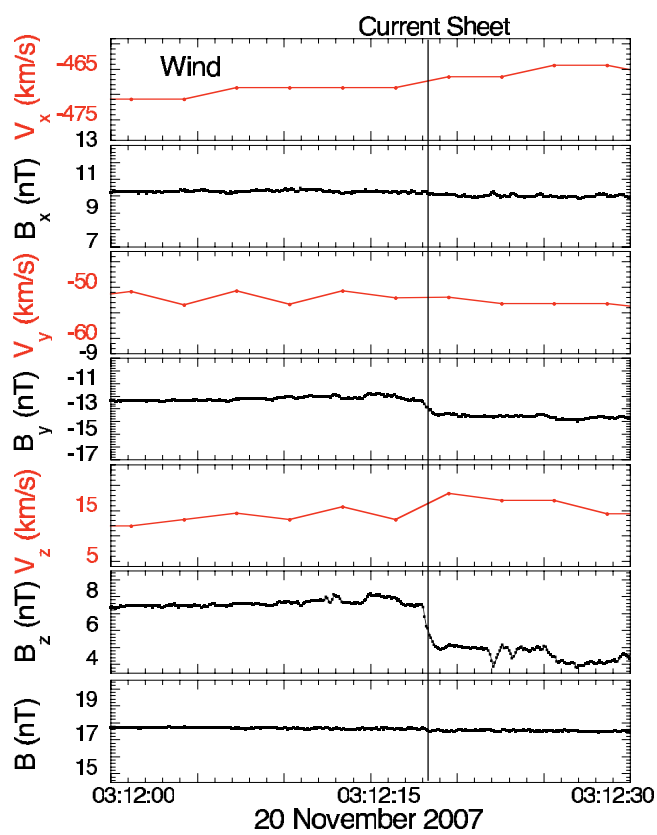

Figure 5. Solar wind velocity (at 3-s resolution) and magnetic field (at 92-ms resolution) data from Wind in GSE coordinates for a 30-s interval within the ICME/cloud on 20 November 2007. The vertical line marks a simple, thin current sheet associated with a field rotation of 9°.

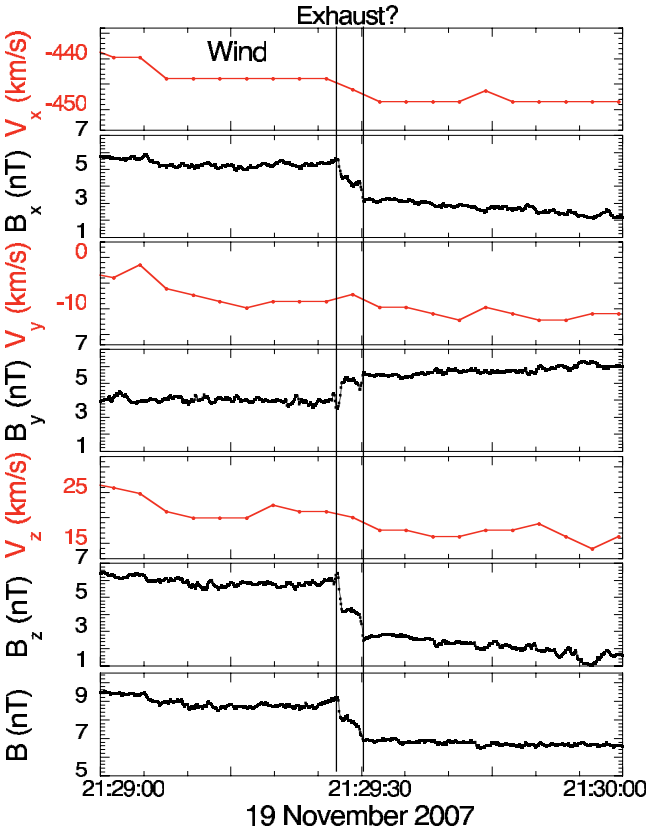

Figure 6. Solar wind velocity (at 3-s resolution) and magnetic field (at 92-ms resolution) data from Wind in GSE coordinates for a 1-min interval within the compressed sheath ahead of the ICME/cloud on 19 November 2007. The vertical lines mark the edges of an apparently bifurcated current sheet and probable reconnection exhaust associated with a field rotation of 31°.

was clearly not bifurcated, indicating that it almost certainly did not contain an undetected reconnection exhaust.

[13] In contrast to the thin, single-step field rotations shown in Figures 4 and 5, Figure 6 shows plasma and magnetic field data encompassing a clear double-step field rotation of 31° that was swept past Wind in 2.94 s and that thus had a maximum width of 1.31×10^3 km ($\sim 25\ c/\omega_{pi}$). This field rotation was not well resolved by the 3-s plasma measurement and there is no evidence in the plasma data for accelerated plasma in association with this event. Nevertheless, the magnetic field data strongly suggest that plasma measurements made at a comparable cadence as the 92-ms magnetic field measurements would have revealed this to be a reconnection exhaust.

3. Discussion

[14] Table 1 provides information on the 11 definite reconnection exhausts identified in the combined 3-s plasma and magnetic field data from Wind on 19 and 20 November 2007. The exhausts were distributed as follows: two in the slow wind ahead of the forward shock; two in the compressed sheath ahead of the ICME/cloud; five within the ICME/cloud; one at the trailing edge of the ICME/cloud; and one in the compressed sheath behind the ICME. At 92-ms resolution all of these exhausts were characterized by double-step magnetic field rotations, as in the examples shown in Figures 3 and 4. As is generally the case in the solar wind, the large majority of these exhausts were swept past the spacecraft in less than 100 s, corresponding to exhaust widths $<\sim 4 \times 10^4$ km. The 2143:36 UT event on 19 November, with a maximum width of 1.0×10^3 km ($\sim 18\ c/\omega_{pi}$), is the narrowest exhaust jet yet identified in the combined 3-s Wind plasma and magnetic field data. Consistent with previous work, the large majority of these exhausts were associated with local magnetic field shear angles <90°, indicating that the guide field (the non-antiparallel component) typically exceeded the antiparallel component in these events. The first three exhausts on 20 November, which occurred within the ICME/cloud, were all associated with local field shear angles <18°, the smallest local field shear angles identified so far in association with reconnection exhausts in the solar wind. Indeed, all of the exhausts identified within the ICME/cloud were associated with relatively small (<37°) local field shear angles. (Geometrically, reconnection is possible for a wide range of magnetic field shear angles. The preponderance of reconnection events associated with small field shear angles in the solar wind in general and within magnetic clouds in particular simply reflects the preponderance of thin current sheets in those environments that are associated with relatively small field shear angles.) The exhaust at 1146:16 UT on 20 November occurred at the back edge of the ICME/cloud. In that particular case the reconnection was analogous to reconnection at Earth's magnetopause in that it occurred at the boundary of a magnetic obstacle downstream from a reverse shock. We have previously shown [*Gosling et al.*, 2007b] an example of a reconnection exhaust at the leading edge of an ICME following a

Table 1. Reconnection Exhausts Observed by Wind on 19 and 20 November 2007

Date (mm/dd/yy)	Start Time (hhmm:ss)	Width (s)	Width (10^3 km)	Width (c/ω_{pi})	Shear (deg)	Bifurcated?
11/19/07	0225:03	112	44.8	361	71	Yes
11/19/07	0917:47	113	41.8	290	38	Yes
11/19/07	1949:04	7.36	3.3	64	114	Yes
11/19/07	2143:36	2.3	1.0	18	79	Yes
11/20/07	0315:28	6.63	3.1	28	17	Yes
11/20/07	0319:43	9.38	4.4	43	15	Yes
11/20/07	0414:18	10.4	5.1	52	17	Yes
11/20/07	0841:03	6.81	3.2	42	26	Yes
11/20/07	0940:43	72.2	33.7	562	37	Yes
11/20/07	1146:16	36	17.2	269	79	Yes
11/20/07	1257:22	63	29.0	403	95	Yes

Table 2. Current Sheets Not Resolved by 3-s Plasma Measurement

Date (mm/dd/yy)	Start Time (hhmm:ss)	Width (s)	Width (10^3 km)	Width (c/ω_{pi})	Shear (deg)	Bifurcated?
11/19/07	0001:55	4.33	1.81	15	57	No
11/19/07	0006:27	0.92	0.38	3	22	No
11/19/07	1454:15	5.4	2.04	16	55	No
11/19/07	1738:41	2.1	0.90	13	29	Yes
11/19/07	1824:20	2.5	1.09	19	20	No
11/19/07	1949:50	0.74	0.33	7	63	No
11/19/07	2016:20	1.75	0.78	17	40	No
11/19/07	2027:06	1.29	0.58	13	49	No
11/19/07	2028:10	1.75	0.78	17	54	Perhaps
11/19/07	2029:21	5.05	2.24	51	74	Perhaps
11/19/07	2129:27	2.94	1.31	25	31	Yes
11/20/07	0312:17	1.02	0.48	4	9	No
11/20/07	0440:45	1.56	0.76	9	14	No
11/20/07	1049:24	0.45	0.21	4	12	No
11/20/07	1149:03	2.85	1.34	17	123	No
11/20/07	1203:17	3.22	1.55	22	124	Yes
11/20/07	1244:07	3.68	1.69	25	64	No
11/20/07	1308:39	3.77	1.83	27	102	No
11/20/07	1357:39	1.29	0.61	8	43	No
11/20/07	1403:03	3.32	1.61	22	55	Perhaps
11/20/07	1403:40	3.41	1.67	23	57	No
11/20/07	1607:17	1.39	0.69	9	42	No
11/20/07	1723:00	2.21	1.07	13	65	No
11/20/07	1723:35	1.28	0.65	8	33	No
11/20/07	2019:36	2.94	1.43	16	57	No
11/20/07	2019:43	1.55	0.75	9	23	No
11/20/07	2336:12	1.75	1.02	6	8	No

forward shock and have identified a number of similar events in the data at other times.

[15] We have surveyed the 3-s magnetic field data for 19 and 20 November 2007 to identify current sheets that were sufficiently thin that they were not well resolved by the 3-s 3DP plasma measurement. Examples of such thin current sheets are shown in Figures 4, 5, and 6. In practice, we limited the list of thin current sheets in Table 2 to the 27 current sheets with field rotations >8° and that were crossed in less than 6 s. All such current sheets identified in this 2-day interval were well resolved by the ~92 ms magnetic field measurement, the thinnest current sheet being crossed in 0.45 s and having a maximum width of 2.1×10^2 km (~4 c/ω_{pi}). As illustrated in Figure 7, local field shear angles for the 27 thin current sheets identified ranged from 8° to 124° with the smallest local field shear angles generally being associated with the thinnest current sheets, consistent with results reported by *Vasquez et al.* [2007] for current sheets in the solar wind in general. The large majority (21) of these current sheets were clearly not bifurcated and therefore were almost certainly not associated with reconnection exhausts. All 21 of these relatively simple current sheets presumably were insufficiently thin to trigger reconnection. Of the other six relatively thin current sheets, all of which occurred within the sheaths immediately ahead of and behind the ICME/cloud, three were clearly bifurcated and the other three were probably bifurcated. If we include all six of these latter field rotations as being associated with reconnection exhausts, then Wind encountered at least 17 reconnection exhausts in this 2-day interval.

[16] Models indicate that magnetic reconnection occurs in thin current sheets having thicknesses comparable to or smaller than an ion inertial length, c/ω_{pi}, which typically is of the order of 50–200 km in the solar wind at 1 AU. Most current sheets in the solar wind at 1 AU are thicker than that [e.g., *Vasquez et al.*, 2007] and thus, presumably, cannot trigger reconnection. It is probably significant that all of the current sheets identified in the 2-day interval of the present study were well resolved in the 92 ms magnetic field data, the thinnest current sheets observed being crossed in 0.45 s or longer and having thicknesses of 3–4 c/ω_{pi}. These thinnest of the thin current sheets were all associated with simple, single-step magnetic field rotations, indicating the absence of reconnection at those current sheets. Since a 400 km/s solar wind travels 36.8 km in 92 ms, one should be able to observe and resolve even thinner simple current sheets in the 92 ms magnetic field data if such current sheets exist unaltered by reconnection. Once reconnection occurs, of course, a current sheet broadens with distance from the reconnection site as it is bifurcated by the Alfvénic disturbances propagating parallel and antiparallel to $\boldsymbol{B}$ on reconnected field lines. It thus may be that all current sheets originally thinner than ~3 c/ω_{pi} in this 2-day interval had already been disrupted by reconnection and were observed instead as considerably thicker bifurcated current sheets and reconnection exhausts. More extensive observations reveal that current sheets thinner than ~3 c/ω_{pi} are relatively rare in the solar wind in general [*Vasquez et al.*, 2007]. This suggests that such ultrathin current sheets typically are quickly disrupted by magnetic reconnection.

[17] Finally, we note that there is considerable evidence that the so-called neutral sheet in Earth's magnetotail at times becomes bifurcated [e.g., *Sergeev et al.*, 1993; *Hoshino et al.*, 1996; *Nakamura et al.*, 2002; *Runov et al.*, 2003; *Asano et al.*, 2003, 2005]. Some such bifurcation events are associated with accelerated plasma flows and, particularly at distances 50–125 Earth radii downtail, have been interpreted [e.g., *Hoshino et al.*, 1996] in terms of

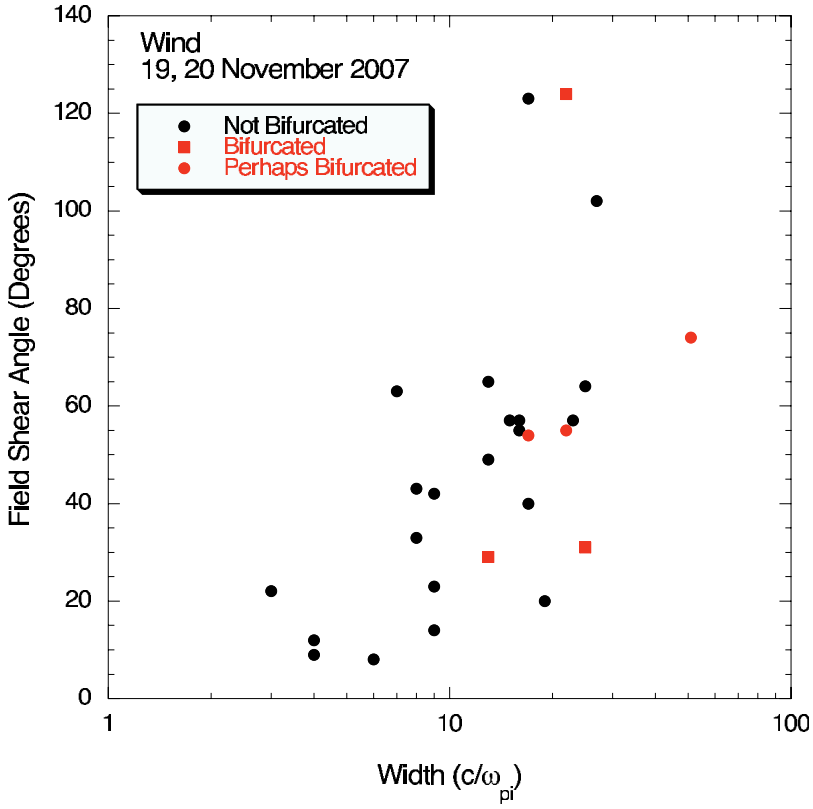

Figure 7. Scatterplot of magnetic field shear angle versus maximum local current sheet width (in units of ion inertial length) for the 27 thin current sheets not well resolved by the 3-s 3DP plasma measurement.

Petschek-type reconnection exhausts from a distant neutral line in a manner similar to that employed for the solar wind events discussed here and in our previous papers. Other bifurcation events in the magnetotail have no obvious association with accelerated plasma flows confined to the current sheet and are observed primarily at times when the neutral sheet thins down to a thickness of the order of c/ω_{pi}. A number of different models invoking processes other than magnetic reconnection have been developed to explain such bifurcations in very thin current sheets in the magnetotail. Examples include models invoking effects associated with pressure anisotropy [*Cowley*, 1978; *Sitnov et al.*, 2003], ion-ion kink instabilities [*Karimabadi et al.*, 2003], and ion particle dynamics [*Zelenyi et al.*, 2003]. It remains to be seen if any of these or related models are applicable to ultrathin current sheets in the solar wind, but current sheets with thicknesses of the order of c/ω_{pi} appear to be relatively rare in the solar wind at 1 AU and bifurcated current sheets identified to date have all been thicker than 12 c/ω_{pi}, where such models may not be applicable.

4. Summary

[18] This paper has provided a smorgasbord of results concerning reconnection exhausts and thin current sheets in the solar wind during a 2-day interval in November 2007. Below we highlight the main new results.

[19] 1. We have identified an unusually large number (11) of reconnection exhausts in this 2-day interval, all of which were associated with the double-step magnetic field rotations that are characteristic of bifurcated current sheets.

[20] 2. Despite the relatively smooth magnetic field rotation that characterizes a magnetic cloud, five of these exhausts occurred within the ICME/magnetic cloud embedded in this 2-day interval. All of these exhausts were associated with relatively small (<37°) local field shear angles, including the three smallest (<18°) local field shear angles yet identified in association with reconnection exhausts in the solar wind.

[21] 3. We have made the first identification of a reconnection exhaust on the trailing edge of a magnetic cloud. That event was analogous to reconnection at Earth's magnetopause in that it occurred at the boundary of a magnetic obstacle downstream from a reverse shock in the solar wind.

[22] 4. Many current sheets in the solar wind are not resolved by the 3-s measurement cadence of the 3DP plasma instrument on Wind. We identified 27 such current sheets in this 2-day interval. All of those current sheets were well resolved with the 92 ms magnetic field measurement and none were thinner than $\sim$3 c/ω_{pi}.

[23] 5. At least three, and possibly six, of those 27 thin current sheets contained the double-step field rotations characteristic of reconnection exhausts in the solar wind, indicating that the underlying current sheets had probably been disrupted by reconnection and that reconnection is almost certainly more prevalent in the solar wind than can be revealed by a combined 3-s plasma and magnetic field measurement cadence.

[24] **Acknowledgments.** We thank R.P. Lepping and R. P. Lin and the CDAWeb for making available the 92-s and 3-s data used in this paper and the referees for some useful suggestions. Work at the University of Colorado was supported by NASA grant NNG06GC27G and the NASA TR&T program.

[25] Amitava Bhattacharjee thanks Gaetano Zimbardo and another reviewer for their assistance in evaluating this paper.

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