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Petschek-type magnetic reconnection exhausts in the solar wind well inside 1 AU: Helios

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[1] Petschek-type reconnection exhausts can be recognized in solar wind plasma and magnetic field data as accelerated or decelerated plasma flows confined to magnetic field reversal regions. Using that characteristic signature, we have identified 28 reconnection exhausts in the Helios 1 and 2 data, thus extending observations of exhausts associated with local, quasi-stationary reconnection in the solar wind inward to heliocentric distances of 0.31 AU. Most of the exhaust jets identified in the Helios data had the same general physical character as solar wind exhausts observed at greater heliocentric distances and latitudes by ACE, Wind, and Ulysses. The magnitude of the velocity changes from outside to inside the exhausts was generally comparable to, but somewhat less than (by a factor of 0.75 on average), the inflow Alfvén speeds. In a few of the Helios events, plasma number densities within the exhausts were intermediate to densities observed immediately outside, indicating that transitions from outside to inside the exhausts were not always slow-mode-like on both sides. We have identified pairs of closely spaced, but independent, reconnection exhausts bounding regions where the heliospheric magnetic field folded back toward the Sun. We find that plasma and magnetic field conditions in the high-speed wind from coronal holes are not generally favorable for sustained magnetic reconnection and for the formation and propagation of Petschek-type exhausts. Finally, we have not yet identified reconnection events common to both spacecraft, partially because of a relative lack of times when high data rate observations were available from both spacecraft.

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1. Introduction

[2] Magnetic reconnection is one of the fundamental processes controlling the evolution of space, solar, astrophysical and laboratory plasmas (see, for example, *Priest and Forbes* [2000] and the collections of articles in the work of *Hones* [1984] and *Russell et al.* [1990]). Reconnection describes a process that changes the topology of the magnetic field and that ultimately converts magnetic field energy into bulk flow energy and plasma heating. Only recently [*Gosling et al.*, 2005a] have we learned how to identify the clear and unambiguous signature of local, quasi-stationary magnetic reconnection in the solar wind in the form of Petschek-type exhausts, i.e., exhausts of jetting plasma bounded by Alfvén or slow mode waves [*Petschek*, 1964; *Levy et al.*, 1964], emanating from reconnection sites. The exhausts are identified in solar wind observations as brief (usually minutes) intervals of Alfvénic accelerated or decelerated plasma flow confined to magnetic field reversal regions that usually take the form of bifurcated current sheets. The overall transitions from outside to inside the exhausts typically are slow-mode-like on both sides, being characterized by field rotations, increases in proton temperature and number density, and decreases in magnetic field strength, in addition to plasma acceleration/deceleration. In essence, an encounter with a reconnection exhaust in the solar wind typically appears as an encounter with a closely spaced forward-reverse slow-mode wave pair [*Gosling et al.*, 2006], somewhat akin to the much more widely separated forward-reverse fast-mode wave pairs bounding corotating stream interaction regions in the solar wind [e.g., *Gosling and Pizzo*, 1999]. The common presence of interpenetrating, field-aligned ion beams, intermediate electron temperatures, and intermediate magnetic field orientations within these events demonstrates magnetic connection across them, as expected for Petschek-type exhausts.

[3] The solar wind typically carries the exhausts past an observing spacecraft on a timescale of 1 to 20 min so that local exhaust widths usually are of the order of $\sim 5 \times 10^5$ km or less. These widths suggest that the local plasma and field in a typical exhaust jet has propagated for ~1.3 days prior to encounter and at the time of observation is $\sim 4.6 \times 10^6$ km away from the reconnection site [*Gosling et al.*, 2006]. Numerical simulations indicate that a bulged, plasmoid-like structure should form on the leading edge (in the direction of the jetting plasma's motion) of an exhaust as a result of

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the interaction of the exhaust jet with the ambient plasma into which it propagates [e.g., *Scholer*, 1988; *Ugai*, 1995]. That interaction produces a compression and deflection of the ambient plasma that propagates ahead of the exhaust as well as a compression and deceleration of the leading edge of the exhaust jet. Such compressive effects, which should be most apparent in the nearby ambient plasma, are not obvious in observations of solar wind exhausts reported to date. This leads us to conclude that the spacecraft seldom, if ever, encounter the leading edge of an exhaust, but rather typically encounter the extended jet well behind the leading edge bulge. The same is true for the observations reported in this paper.

[4] Thus far more than 50 encounters with reconnection exhausts have been identified in the ACE [*Gosling et al.*, 2005b] and Wind [*Phan et al.*, 2006; *Davis et al.*, 2006] solar wind plasma and magnetic field data in the ecliptic plane near 1 AU and more than 90 similar events have been identified in the Ulysses data at heliocentric distances ranging from 1.4 to 5.4 AU and heliographic latitudes ranging from S79 degrees to N65 degrees [*Gosling et al.*, 2006]. Reconnection exhausts are observed almost exclusively in either low-speed solar wind or in association with interplanetary coronal mass ejections (ICMEs) in plasmas predominantly having low (<1 and often $\ll 1$) proton beta. The events usually occur at relatively thin current sheets separating solar wind regions having distinctly different plasma and magnetic field characteristics. That is, reconnection occurs at tangential discontinuities in the solar wind such as, for example, the extensive interfaces separating ICME and ambient wind plasma, interfaces between open and closed field lines within ICMEs, the extensive heliospheric current sheet separating regions of opposite magnetic polarity [see, e.g., *Gosling et al.*, 2005b, Figure 5], and current sheets separating regions of fields folded back toward the Sun [e.g., *Kahler et al.*, 1998] from regions characterized by normal Parker-type fields [*Parker*, 1963]. Local magnetic field shears across the exhausts generally fall in the range 90 to 180 degrees, suggesting significant guide fields (component reconnection) in many of these events. In one case, ACE and Wind detected oppositely directed exhaust jets from a site between the two spacecraft [*Davis et al.*, 2006], thus providing strong confirmation that these events are indeed a product of magnetic reconnection, and also in that particular case strongly indicating the presence of a substantial guide field at the reconnection site. Observations of suprathermal electron distributions during a rare encounter with an exhaust at the heliospheric current sheet [*Gosling et al.*, 2005b] showed that dropouts in the suprathermal electron strahl are at times signatures of magnetic disconnection from the Sun, as has long been speculated [e.g., *McComas et al.*, 1989]. Perhaps surprisingly, preliminary studies suggest that reconnection in the solar wind is not a significant source of suprathermal or energetic particles there [*Gosling et al.*, 2005c].

[5] Multispacecraft observations by ACE and Wind (and, at times, Cluster) at 1 AU demonstrate that the exhausts result from local quasi-steady reconnection at extended 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]. These estimates are only lower limits, conscribed by the relatively limited spatial separations available for ACE and Wind, both stationed in the near-Earth vicinity. Although the ACE/Wind separations are large compared to separations available for studying reconnection in Earth's magnetosphere, they are small compared to the scale sizes of current sheets and reconnection X-lines in the solar wind. In order to extend these estimates to larger scale sizes and longer times, larger spacecraft separations are required. Thus we have begun a study to identify and analyze reconnection exhausts in plasma and magnetic field data from the more widely separated Helios 1 and 2 spacecraft. Our purpose here is to report initial results of that investigation, which has extended observations of reconnection exhausts in the solar wind to within 0.31 AU of the Sun.

2. Spacecraft and Data

[6] The nearly identical Helios spacecraft were launched into highly elliptical orbits about the Sun approximately in the ecliptic plane with a perihelion heliocentric distance of 0.29 AU and aphelion distance of 1 AU. Helios 1 was launched on 10 December 1974 and Helios 2 was launched a little more than a year later on 15 January 1976. Helios 1 survived until March 1996, whereas Helios 2 failed on 3 March 1980. Owing to their respective launch dates, the lines of apsides for the Helios 1 and 2 orbits are inclined relative to one another by about 36 degrees, providing a variety of radial and longitudinal spacecraft separations that are considerably greater than those available from the ACE/Wind combination. In high data rate, three-dimensional ion moments (density, velocity, temperature) were obtained at a cadence of 41 s, whereas the DC magnetic field was measured at a cadence up to 5 Hz. Such cadences are more than adequate to resolve reconnection exhausts in the solar wind; however, considerably less than half of the Helios data were obtained in high data rate. In the present paper we show magnetic field data at the same temporal cadence as the plasma observations. Our study is restricted to the interval from 10 December 1974 through 25 June 1981, the last date for which verified magnetic field data from Helios 1 were available to us. Descriptions of the plasma and magnetic field instrumentation on Helios can be found in the work of *Rosenbauer et al.* [1981], *Schwenn et al.* [1975] and *Musman et al.* [1975] and discussions of the Helios orbits can be found in the work of *Marsch and Schwenn* [1990].

3. Observations

3.1. A Representative Helios Encounter With a Reconnection Exhaust Near 1 AU

[7] Figure 1 shows in R, T, N coordinates a brief encounter of Helios 2 with an accelerated flow event within a field reversal region on 27 January 1976 at 0.97 AU. Here the $+R$ direction is radial out from the Sun, the $+T$ direction is in the direction of Earth's motion about the Sun, and the $+N$ direction completes a right-handed system. The encounter was marked by a large (141 degrees) rotation in the magnetic field, $\boldsymbol{B}$, that occurred in two distinct steps and by substantial changes in all three velocity, $\boldsymbol{V}$, components. The changes in $\boldsymbol{V}$ and $\boldsymbol{B}$ were correlated with one another at the leading edge of the event and were anticorrelated at the

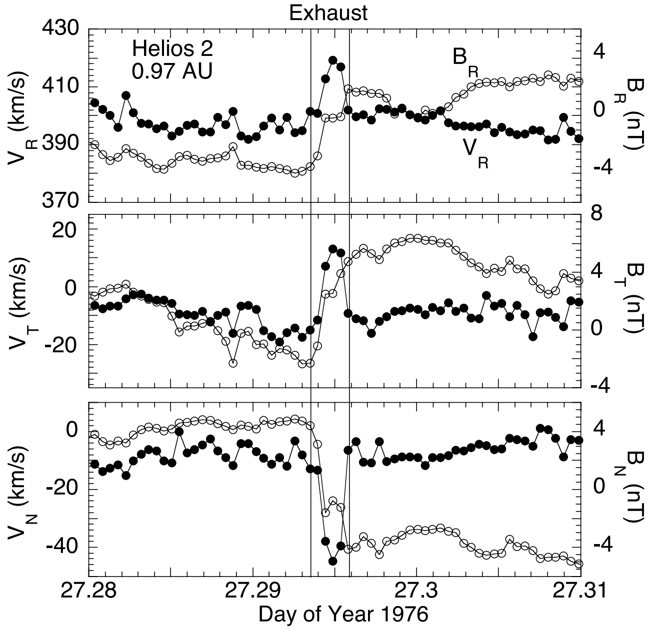

Figure 1. Solar wind magnetic field (open dots) and proton flow velocity (closed dots) components in *R*, *T*, *N* coordinates as observed by Helios 2 in a 43.2-min interval on 27 January 1976 at 0.97 AU. Both magnetic field and plasma data are shown at the cadence of the plasma measurements (41 s). Vertical lines bracket a field reversal region and accelerated flow event associated with a reconnection exhaust.

trailing edge. Such pairs of coupled changes in ***V*** and ***B*** are the characteristic signature by which we identify reconnection exhausts in the solar wind. In this case those coupled changes and the increase in ΔV_r indicate that Alfvén or slow mode waves propagating away from the Sun in opposite directions along reconnected magnetic field lines bounded the exhaust. The magnitude of the maximum change in velocity, $\Delta \boldsymbol{V}$, from outside to inside the exhaust (∼47 km/s) was comparable to, but slightly less than, the average external Alfvén speed (54 km/s, see Figure 2). Figure 2 also demonstrates that the exhaust was characterized by increases in proton number density, proton temperature, and proton beta and by decreases in magnetic field strength and local Alfvén speed. Thus the changes in plasma and magnetic field parameters from outside to inside the exhaust were slow-mode-like on both sides. In addition, Figure 2 reveals that the 27 January 1976 exhaust occurred within low-speed solar wind having low proton beta and having slightly different plasma and magnetic field characteristics on opposite sides. All of the above are also characteristic of reconnection exhausts identified in ACE, Ulysses, and Wind solar wind data [e.g., *Gosling et al.*, 2005a, 2006; *Phan et al.*, 2006]. Using the observed solar wind speed of ∼400 km/s and the observed crossing time of ∼5 min, we find that the exhaust was no wider than 1.2×10^5 km where sampled by Helios 2.

3.2. Two Reconnection Exhausts Observed Near Orbit Perihelion

[8] By searching for accelerated and decelerated flow events confined to field reversal regions and having the characteristic pairs of coupled changes in ***V*** and ***B*** (anti-correlated on one side and correlated on the other) noted above, we have identified reconnection exhausts, nominally similar to the event shown in Figures 1 and 2, at all heliocentric distances sampled by Helios 1 and 2. Figures 3 and 4 show data for a reconnection exhaust observed by Helios 1 at 0.43 AU on 29 May 1981 and Figures 5 and 6 show data for an exhaust observed by Helios 1 at 0.31 AU

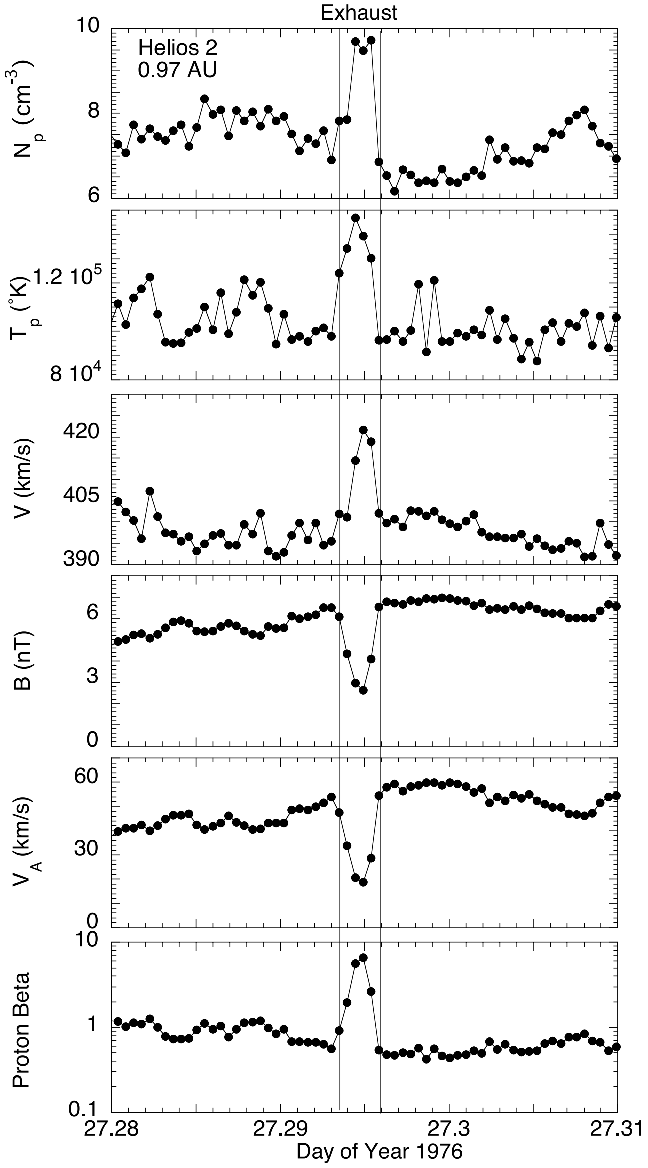

Figure 2. Selected plasma and magnetic field data from Helios 2 in a 43.2-min interval on 27 January 1976 shown at the cadence of the plasma data. From top to bottom the parameters plotted are the proton number density, the proton temperature, the solar wind speed, the magnetic field strength, the local Alfvén speed, and the proton beta (ratio of proton thermal pressure to the magnetic field pressure). Vertical lines bracket the reconnection exhaust.

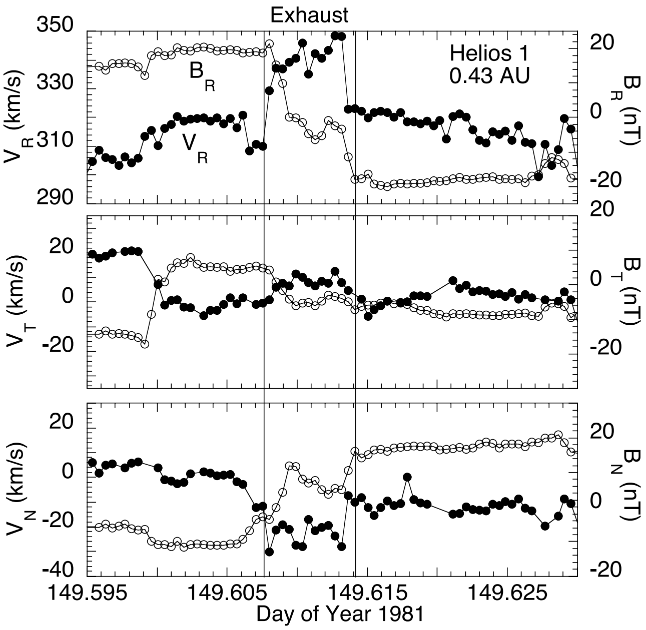

Figure 3. Solar wind magnetic field (open dots) and proton flow velocity (closed dots) components in *R*, *T*, *N* coordinates as observed by Helios 1 at 0.43 AU in a 50.4-min interval on 29 May 1981. Both magnetic field and plasma data are shown at the cadence of the plasma measurements (41 s). Vertical lines bracket a reconnection exhaust.

on 22 September 1975. The former event was an antisunward directed exhaust, whereas the latter was a sunward directed exhaust. Both exhausts were observed in the low-speed solar wind and were carried away from the Sun by the super-Alfvénic solar wind flow. The maximum $|\Delta \boldsymbol{V}|$ was 50 km/s in the 29 May 1981 event and was 11 km/s in the 22 September 1975 event, comparable to, but somewhat less than, the average external Alfvén speeds, V_A, of 68 km/s and 19 km/s, respectively, in those events. Maximum local widths of the events were 2.3×10^5 km and 8×10^4 km, respectively.

[9] The 22 September 1975 event differed from most reconnection exhausts observed in the solar wind in that no clear increases in proton number density and proton temperature were detected within the exhaust and the event occurred in solar wind having proton beta >1. We note, however, that the proton number density within the exhaust was comparable to that before the event and greater than that after the event. Similar density signals have been observed in several other exhausts in the Helios data and also in a few exhausts observed at greater heliocentric distances by ACE and Ulysses. This indicates that the transitions from outside to inside reconnection exhausts in the solar wind are not always slow-mode-like, even though most such transitions are.

3.3. A Pair of Reconnection Exhausts Associated With the Edges of an Interval of Folded Magnetic Field

[10] Occasionally, reconnection exhausts in the solar wind occur as pairs of relatively closely spaced events. We have identified such pairs of events in the Helios 1 data on 15 December 1974 and in the Helios 2 data on 30 January 1976. Figures 7 and 8 show plasma and magnetic field data encompassing the 30 January 1976 events, which were observed when Helios 2 was at 0.97 AU. Both decelerated flow events filled field reversal regions and both exhibited the characteristic pairs of coupled changes in $\boldsymbol{V}$ and $\boldsymbol{B}$ by which we identify reconnection exhausts in the solar wind. They also were both associated with small increases in proton temperature and with substantial decreases in $|\boldsymbol{B}|$; however, the first event included

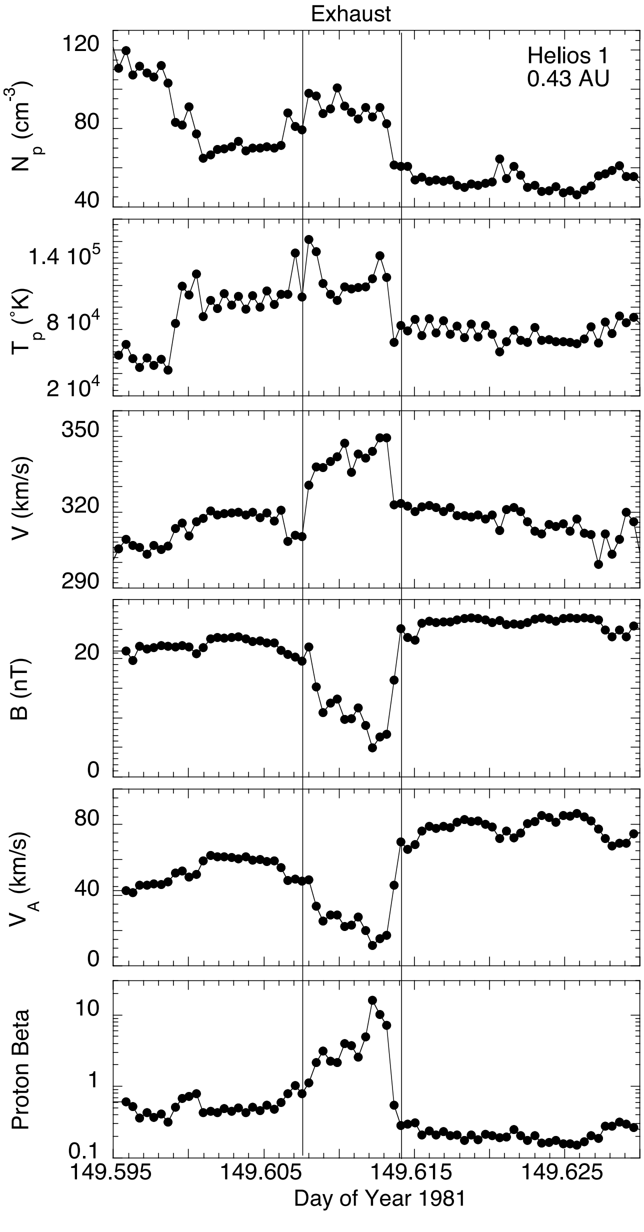

Figure 4. Selected plasma and magnetic field data from Helios 1 in a 50.4-min interval on 29 May 1981 shown at the cadence of the plasma data. From top to bottom the parameters plotted are the proton number density, the proton temperature, the solar wind speed, the magnetic field strength, the local Alfvén speed, and the proton beta (ratio of proton thermal pressure to the magnetic field pressure). Vertical lines bracket the reconnection exhaust.

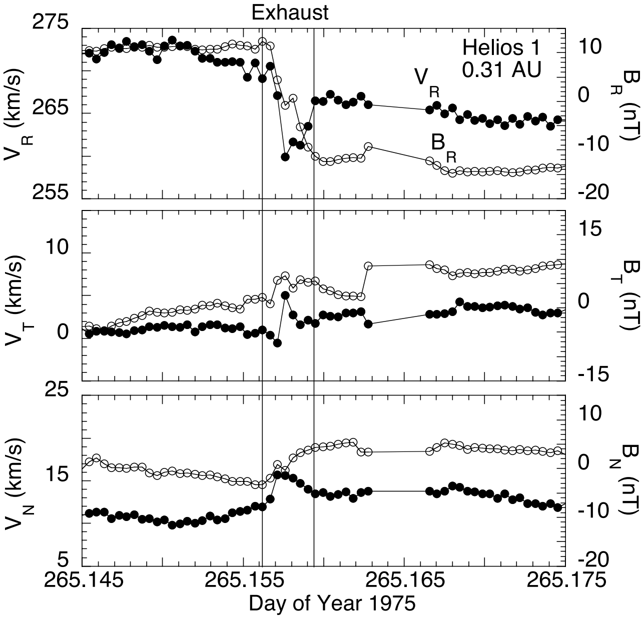

Figure 5. Solar wind magnetic field (open dots) and proton flow velocity (closed dots) components in *R*, *T*, *N* coordinates as observed by Helios 1 at 0.31 AU in a 43.2-min interval on 22 September 1975. Both magnetic field and plasma data are shown at the cadence of the plasma measurements (41 s). Vertical lines bracket a reconnection exhaust.

an increase in density, whereas the second one did not. The maximum $|\Delta V|$ from outside to inside these exhausts were 22 km/s and 19 km/s, respectively, somewhat less than the average external Alfvén speeds (26 km/s and 32 km/s, respectively).

[11] As is usually the case for exhaust pairs observed in the solar wind by ACE and Ulysses, the 30 January 1976 pair bracketed a short-lived (~40-min) reversal in the polarity of ***B***. This short-lived field reversal was not associated with a pair of crossings of the heliospheric current sheet, HCS, which are always marked by simultaneous reversals in both the magnetic field polarity and the flow polarity (parallel or antiparallel to ***B***) of the suprathermal electron strahl that carries the solar wind electron heat flux away from the Sun. In contrast, our examination of the Helios 2 suprathermal electron data for these events (not shown) reveals that the strahl flow polarity did not change across either of the pair of field reversals evident in Figure 7. This brief (~40-min) interval of reversed field polarity was thus associated with an encounter with a solar wind region containing fields folded back toward the Sun. The same is true for the 15 December 1974 exhaust pair observed by Helios 1. Folded field intervals like this, which are relatively common in the solar wind [*Pilipp et al.*, 1987; *Kahler and Lin*, 1994; *Kahler et al.*, 1998], may result from interchange reconnection (i.e., reconnection between open and closed field lines) relatively close to the Sun [e.g., *Crooker et al.*, 2002]. However, it is unlikely that the pair of reconnection exhausts observed by Helios 2 is a signature of interchange reconnection close to the Sun. Rather, those exhausts must have resulted from later local reconnections of ordinary open field lines with previously folded field lines since both exhausts were directed sunward. Finally, we wish to emphasize that although exhaust pairs are usually found in association with the edges of regions of folded fields, most folded field regions in the solar wind are not bounded by exhaust pairs.

3.4. Exhaust Statistics

[12] Table 1 provides dates and times of the 28 reconnection exhausts we have identified in the Helios 1 and 2 data, along with information on spacecraft location, the magnitudes of the field rotations across the exhausts, the

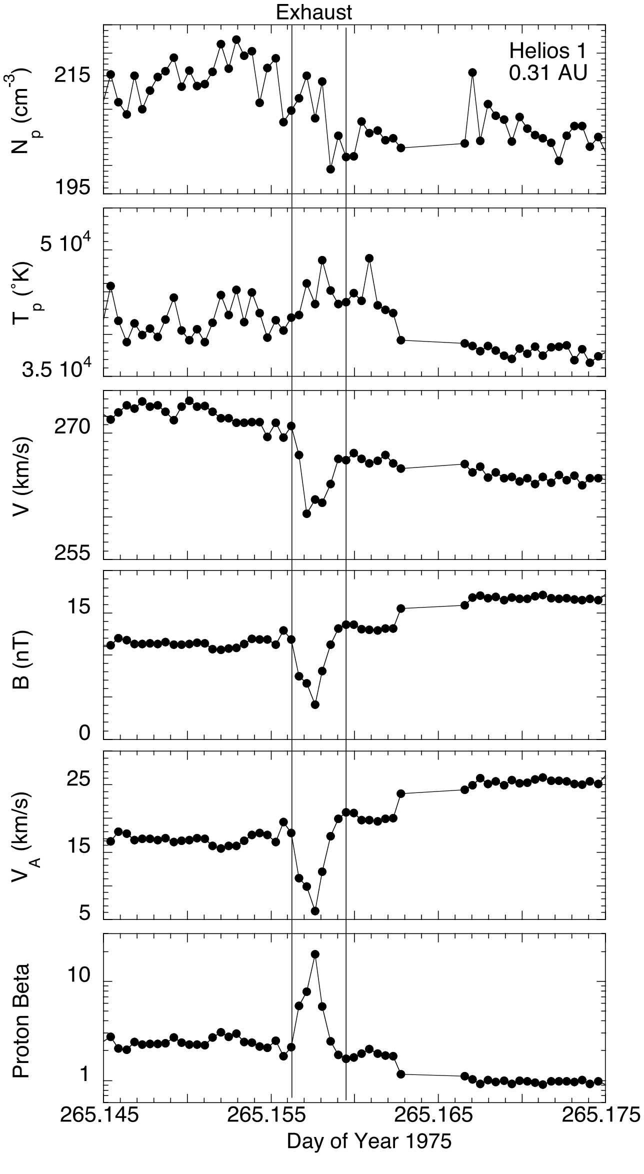

Figure 6. Selected plasma and magnetic field data from Helios 1 in a 43.2-min interval on 22 September 1975 shown at the cadence of the plasma data. From top to bottom the parameters plotted are the proton number density, the proton temperature, the solar wind speed, the magnetic field strength, the local Alfvén speed, and the proton beta (ratio of proton thermal pressure to the magnetic field pressure). Vertical lines bracket the reconnection exhaust.

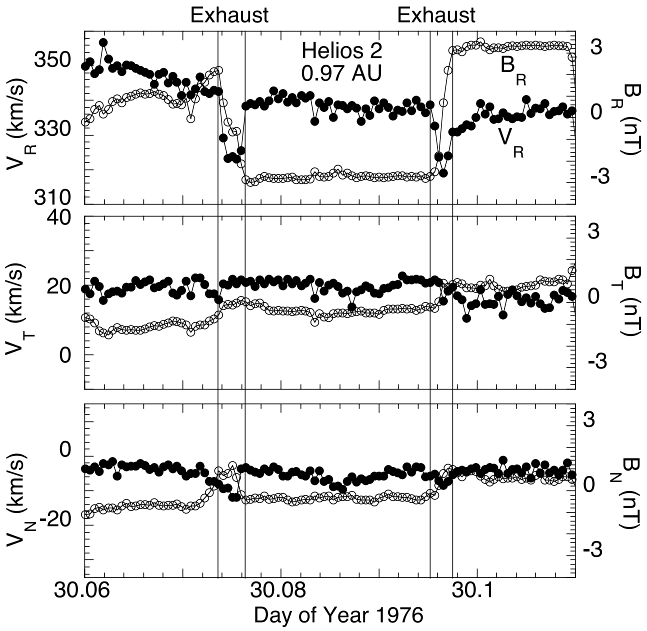

Figure 7. Solar wind magnetic field (open dots) and proton flow velocity (closed dots) components in *R*, *T*, *N* coordinates as observed by Helios 2 at 0.97 AU in a 72-min interval on 30 January 1976. Both magnetic field and plasma data are shown at the cadence of the plasma measurements (41 s). Vertical lines bracket a pair of reconnection exhausts.

average proton betas immediately external to the exhausts, the solar wind speeds at the times of the events, and the ratios of the maximum $|\mathbf{\Delta V}|$ from outside to inside the exhausts to the average of the external Alfvén speeds. Owing (1) to the fact that the spacecraft spend more time at large than at small heliocentric distances and (2) that a greater percentage of the data were obtained at high telemetry rate at large than at small heliocentric distances, a large fraction of the reconnection exhausts we have identified in the Helios data were encountered at heliocentric distances >0.7 AU. Nevertheless, we have identified reconnection exhausts over almost the full range of heliocentric distances sampled by Helios 1 and 2. We find that exhausts were convected past the spacecraft by the solar wind on timescales ranging from about 2 min to almost 2 hours, with the vast majority of exhaust crossings occurring on timescales of 12 min or less. Thus the vast majority of the exhausts had local widths less than $\sim 3 \times 10^5$ km, comparable to what has typically been observed by ACE, Wind, and Ulysses. However, the 21 June 1979 event had an estimated local width of 3×10^6 km, making it the broadest exhaust we have yet identified at any distance from the Sun.

[13] Table 1 also reveals that local magnetic field shears, external proton betas, and solar wind speeds for the Helios events were comparable to those for events observed by other spacecraft at different distances from the Sun. In particular, observed magnetic field shears across the exhausts ranged from 70 to 179 degrees with the average field shear being ∼138 degrees, the external proton betas ranged from 0.01 to 1.95 with all but two events occurring in beta <1.0 solar wind and the average external beta being 0.35, and the exhausts all occurred in low-speed plasma with the average external solar wind speed for all events being 390 km/s. The last column in Table 1 demonstrates that observed maximum $|\mathbf{\Delta V}|$ from outside to inside the exhausts were generally comparable to, but usually somewhat less than, the external Alfvén speeds, with the average of $|\mathbf{\Delta V}|/V_A$ being 0.75.

[14] Finally, with respect to Table 1, we note that we have not yet identified any events where both spacecraft observed

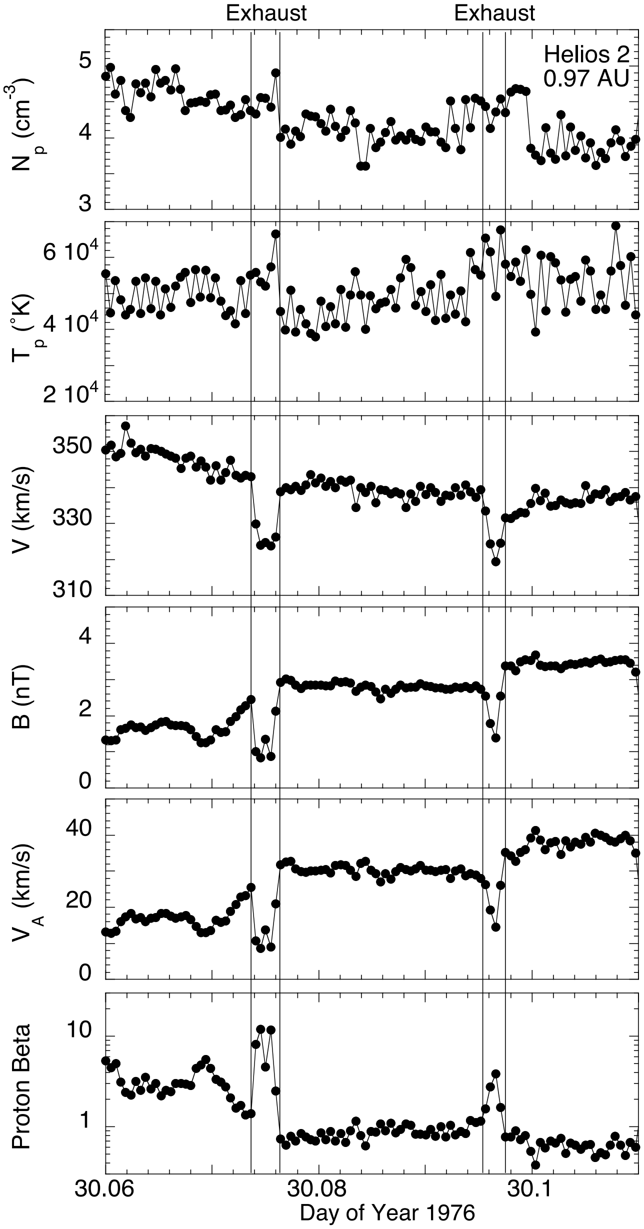

Figure 8. Selected plasma and magnetic field data from Helios 2 in a 72-min interval on 30 January 1976 shown at the cadence of the plasma data. From top to bottom the parameters plotted are the proton number density, the proton temperature, the solar wind speed, the magnetic field strength, the local Alfvén speed, and the proton beta (ratio of proton thermal pressure to the magnetic field pressure). Vertical lines bracket a pair of reconnection exhausts.

Table 1. Reconnection Exhausts Identified in Helios 1 and 2 Data

Year	Day Month	Time, UT	S/C R, AU	Shear, deg	Beta	Speed, km/s	$\|\Delta \mathbf{V}\|/V_A$
1974	15 Dec	1428–1430	H1 0.98	118	0.38	497	0.58
1974	15 Dec	1958–2004	H1 0.98	128	0.35	458	0.93
1975	18 Jan	1338–1348	H1 0.86	151	0.38	532	0.72
1975	7 Feb	0121–0125	H1 0.70	117	0.92	442	1.04
1975	22 Sep	0345–0350	H1 0.31	156	1.95	269	0.58
1975	19 Dec	2052–2100	H1 0.98	132	0.46	350	0.55
1976	19 Jan	0618–0630	H2 0.98	121	0.41	406	1.01
1976	27 Jan	0702–0707	H2 0.97	141	0.57	399	0.87
1976	30 Jan	0146–0151	H2 0.97	160	1.22	342	0.83
1976	30 Jan	0216–0221	H2 0.97	170	0.88	336	0.59
1976	4 Mar	0939–0943	H2 0.77	178	0.22	476	0.32
1976	15 Dec	0134–0139	H2 0.87	143	0.33	328	0.89
1977	5 Apr	2150–2207	H2 0.47	108	0.06	455	0.51
1977	17 Dec	0054–0058	H1 0.87	138	0.46	324	0.98
1978	25 Jan	0652–0658	H2 0.98	146	0.23	352	0.83
1978	26 Feb	0428–0435	H2 0.91	179	0.12	552	0.97
1978	17 Mar	1540–1609	H1 0.76	117	0.19	306	0.62
1979	21 Jun	0107–0304	H1 0.71	152	0.19	421	0.84
1980	3 Jan	1945–1955	H1 0.77	156	0.18	508	1.01
1980	16 Jan	1418–1426	H1 0.87	091	0.10	333	0.56
1980	2 Feb	0033–0039	H1 0.95	070	0.01	312	0.55
1980	12 Apr	1310–1321	H1 0.79	128	0.22	300	0.73
1980	20 Jun	2101–2111	H1 0.54	152	0.09	382	0.58
1981	11 Jan	0729–0735	H1 0.71	079	0.05	301	0.60
1981	31 Jan	0505–0512	H1 0.87	165	0.13	444	0.97
1981	26 Apr	1339–1349	H1 0.80	121	0.15	424	1.00
1981	3 May	0147–0208	H1 0.74	170	0.30	350	0.78
1981	29 May	1434–1444	H1 0.43	167	0.31	319	0.74

the same reconnection exhaust. Indeed, we have not yet identified cases where both spacecraft encountered the same current sheet and were also both acquiring data at a rate adequate to identify reconnection exhausts. This is largely because intervals when high data rate observations were available from both spacecraft were relatively rare.

4. Summary and Discussion

[15] We have searched for and, not unexpectedly, found a number of Petschek-type reconnection exhausts in the Helios 1 and 2 data at essentially all heliocentric distances sampled by the spacecraft, thus extending observational evidence for local, quasi-stationary reconnection in the solar wind into heliocentric distances of 0.31 AU. We have also shown that reconnection exhausts in the solar wind occasionally occur as pairs of exhausts at the edges of solar wind regions containing magnetic fields folded back toward the Sun. We have not yet, however, identified any events where both spacecraft observed the same reconnection exhaust. We have found that reconnection exhausts in the Helios data have the same general character as exhausts observed at different heliocentric distances and latitudes by ACE, Wind, and Ulysses. In particular: (1) the exhausts fill magnetic field reversal regions commonly characterized as bifurcated current sheets; (2) the exhausts are commonly associated with local field rotations ranging from 90 to 180 degrees, suggesting the presence of significant guide fields and component reconnection in a large fraction of these events, although we essentially never actually measure the field shear at the reconnection site itself; (3) both antisunward and sunward directed exhausts are commonly observed, but we have not identified any events where a single spacecraft has encountered both exhausts emanating from a common reconnection site; (4) the magnitude of changes in the flow velocity associated with the exhausts are comparable to, but usually are somewhat less than, the external (inflow) Alfvén speeds; (5) the exhausts typically are convected past the spacecraft on timescales of minutes, indicating that the exhausts are relatively narrow on heliospheric scales in the direction of the current sheet normals; (6) the exhausts occur almost exclusively in the low-speed wind or in association with ICMEs in low (<1) proton beta plasmas, although the proton beta commonly increases substantially within the exhausts; and (7) the overall transitions from outside to inside the exhausts typically are slow-mode-like on both sides, being characterized by increases in proton temperature and proton number density, and decreases in magnetic field strength, in addition to field rotations and plasma accelerations/decelerations.

[16] We have, however, found a few reconnection exhausts lacking clear enhancements in proton number density in the Helios data; several similar events have now been identified in the ACE and Ulysses data as well. Events of this nature typically occur when the exhausts are bounded on opposite sides by different density plasmas, the densities within the exhausts being intermediate to those on the opposite sides. This indicates that, contrary to a conclusion reached in one of our recent papers [*Gosling et al.*, 2006], transitions from outside to inside reconnection exhausts in the solar wind are not always slow-mode-like on both sides, although they usually have that character. In this regard, we note that when reconnection occurs at Earth's magnetopause, plasma densities within the reconnection exhausts are typically comparable to, but somewhat less than, that in the adjacent (high-density) magnetosheath. That is, the densities within the exhausts typically are intermediate to those prevailing on opposite sides of the

magnetopause [e.g., *Gosling et al.*, 1986]. Thus transitions into the magnetopause reconnection exhausts from the magnetosheath side are usually not slow-mode-like either. The lack of a clear density increase within reconnection exhausts at the magnetopause can probably be attributed to the asymmetric nature of the plasmas on opposite sides of the magnetopause. We suspect that density increases within reconnection exhausts in the solar wind do not typically result from compression by slow mode shocks, but rather are a result of plasma interpenetration from opposite sides of the exhausts. Such interpenetration can lead to intermediate internal densities when the densities on opposite sides are different, since plasma density is not a conserved quantity along field lines. Similarly, we have previously mentioned that enhanced proton temperatures within solar wind reconnection exhausts appear to result primarily from interpenetration from opposite sides of the exhausts [*Gosling et al.*, 2005a; *Gosling*, 2005] rather than from compression as predicted by fluid models [e.g., *Petschek*, 1964]. Nevertheless, as we have already mentioned, most transitions from outside to inside reconnection exhausts appear to be slow-mode-like on both sides.

[17] Magnetohydrodynamic theory for symmetric reconnection predicts that the magnitude of the change in velocity from outside to inside a reconnection exhaust should equal the external Alfvén speed based on the antiparallel field component [see, e.g., *Priest and Forbes*, 2000, and references therein]. Since many of the Helios events occurred at field shears considerably less than 180°, it is not surprising that observed magnitudes of the changes in velocity at the exhausts were often considerably less than the external Alfvén speed. However, there is not a strong correlation between values of field shear and $|\boldsymbol{\Delta V}|/V_A$ in Table 1. Our result is consistent with the observation [e.g., *Neugebauer et al.*, 1984; *Goldstein et al.*, 1995] that the velocity changes across rotational discontinuities and Alfvén waves in the normal solar wind are typically somewhat less than is predicted by theory [e.g., *Hudson*, 1970].

[18] Finally, we have noted that almost all Petschek-type reconnection exhausts that we have identified in the Helios, ACE, and Ulysses data have occurred in the low-speed solar wind or in association with ICMEs. We believe there are several reasons why we have not identified such events in the high-speed wind from coronal holes. First, reconnection in the solar wind appears to favor low proton beta, whereas the high-speed solar wind from coronal holes is often high-beta plasma. (It is not altogether clear why reconnection in the solar wind preferentially occurs in low beta plasma, although it has been suggested that the onset of the tearing mode instability, which may initiate reconnection, favors low beta [e.g., *Coroniti and Quest*, 1984].) Second, reconnection in the solar wind occurs at current sheets that are tangential discontinuities separating plasmas usually having small, but distinctly different, characteristics; on the other hand, almost all current sheets in the high-speed wind appear to be associated with steepened Alfvén waves since changes in $\boldsymbol{V}$ and $\boldsymbol{B}$ are commonly either correlated or anticorrelated (depending on the sign of B_r) with one another throughout such current sheets. (See, however, *Neugebauer* [2006] for a nuanced discussion of some of the difficulties in distinguishing steepened Alfvén waves and rotational discontinuities from tangential discontinuities in the solar wind.) Third, in order to sustain reconnection in a quasi-stationary manner and for the disturbance produced by reconnection to propagate as an organized exhaust, a reasonably stable and well-ordered ambient magnetic field is a necessity. Such stable and well-ordered magnetic fields occur frequently in the low-speed wind and within ICMEs, but seldom occur in the Alfvén wave and turbulence-dominated high-speed wind, particularly in the very inner heliosphere. Thus conditions are not generally favorable for sustained, quasi-stationary reconnection and for the formation and propagation of well-organized Petschek-type exhausts in the high-speed wind from coronal holes. There have been suggestions that turbulence should commonly drive reconnection in the high-speed wind [e.g., *Matthaeus et al.*, 2003]. Our observations indicate if turbulence does drive reconnection in the high-speed wind that reconnection does not produce well-organized Petschek-type exhausts that are readily identifiable in the data by the techniques that we have been using.

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