GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L15110, doi:10.1029/2007GL030706, 2007

Prevalence of magnetic reconnection at small field shear angles in the solar wind

J. T. Gosling,[1] T. D. Phan,[2] R. P. Lin,[2] and A. Szabo[3]

Received 16 May 2007; revised 28 June 2007; accepted 18 July 2007; published 15 August 2007.

[1] A study of magnetic reconnection exhausts observed at high (3-s) temporal resolution by the plasma and magnetic field experiments on Wind during March 2006 reveals, unexpectedly, that reconnection in the solar wind occurs most frequently at field shear angles <90°. Owing largely to the relatively low reconnection rates associated with small field shear angles, the corresponding exhausts tend to be quite narrow (<4 × 10^4 km) and typically are convected past the spacecraft by the solar wind flow in <100 s. During March 2006 Wind encountered reconnection exhausts at an average rate of ∼1.5 events/day, a factor of ∼36 greater than has been inferred from previous observations, largely made at considerably lower (∼1-min) temporal resolution.

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

1. Introduction

[2] Observations of roughly Alfvénic accelerated plasma flows confined to magnetic field reversal regions, which usually take the form of bifurcated current sheets, have provided convincing direct evidence for local, quasi-stationary, magnetic reconnection in the solar wind [e.g., *Gosling et al.*, 2005; *Phan et al.*, 2006; *Davis et al.*, 2006]. These so-called reconnection exhausts have been identified almost exclusively in either low-speed solar wind or in association with the interplanetary counterparts of coronal mass ejections (ICMEs) in plasma predominantly having low (<1 and often ≪ 1) proton beta [e.g., *Gosling et al.*, 2006a]. The exhausts are embedded within the solar wind flow and are convected past a spacecraft on time scales ranging from less than a minute [*Huttunen et al.*, 2007] to several hours, corresponding to local exhaust widths ranging up to a maximum of ∼2 × 10^6 km [*Gosling et al.*, 2007a]. Previous studies have reported field shear angles across the exhausts that range from about 70° to 180°, with most probable and median values close to 135° [*Gosling et al.*, 2006a, 2006b; *Huttunen et al.*, 2007].

[3] In our initial study [*Gosling et al.*, 2005] of solar wind reconnection exhausts in the Advanced Composition Explorer (ACE) data we identified only 6 events in 6.5 years; all 6 events occurred within ICMEs, had widths of at least 2 × 10^5 km, and were associated with local field shears >90°. Since then we have developed improved techniques for recognizing solar wind exhausts in the data and have identified an increasing number of events both within ICMEs and in the ordinary low-speed wind. Nevertheless, in an unpublished survey of 9 years of ACE 64-s plasma and magnetic field solar wind observations, we identified only ∼140 exhausts, an average of ∼1.3 events/month. A recent study [*Gosling et al.*, 2007b] of Wind observations of a set of 7 reconnection exhausts that occurred within a 27-hr interval and that were associated with an ICME suggested that reconnection in the solar wind might: (1) frequently occur at field shear angles considerably smaller than 90°, (2) produce substantial numbers of exhausts with widths too small to be resolved by the 64-s sampling cadence of the ACE plasma experiment, and (3) thus occur far more frequently than previously reported. Here we report results of a study of reconnection exhausts in the solar wind using the 3-s plasma and magnetic field data from the 3DP plasma [*Lin et al.*, 1995] and magnetic field [*Lepping et al.*, 1995] experiments on the Wind spacecraft during a randomly chosen month – March 2006 – which occurred during the recent approach to the minimum of the 11-year solar activity cycle.

2. Observations

[4] Figure 1 provides an overview of solar wind conditions measured at 1 AU in March 2006. Several high-speed streams of modest amplitude and width were observed during the 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 heliospheric current sheet (HCS), of which there were at least four during the month, can be recognized in Figure 1 as locations where the field azimuthal angle switched from ∼135° to ∼315° or visa versa. Numerous other current sheets were encountered during the month, some of which produced sharp, but often relatively small, changes in the 1-hr averages of the field azimuth and latitude angles, Φ_B and Θ_B, shown in Figure 1. We have not identified any ICMEs in the March 2006 data.

[5] The jetting plasma associated with a reconnection exhaust in the solar wind is always bounded by rotational discontinuities at which the changes in flow velocity and magnetic field vectors (***V*** and ***B***, respectively) are correlated on one side and anti-correlated on the other; this provides a clear and unambiguous signature by which to recognize the exhausts in the data. Figure 2 shows selected plasma and magnetic field data encompassing two reconnection exhausts observed by Wind on 31 March 2006. The

[1]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, USA.
[2]Space Sciences Laboratory, University of California, Berkeley, California, USA.
[3]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

0094-8276/07/2007GL030706$05.00

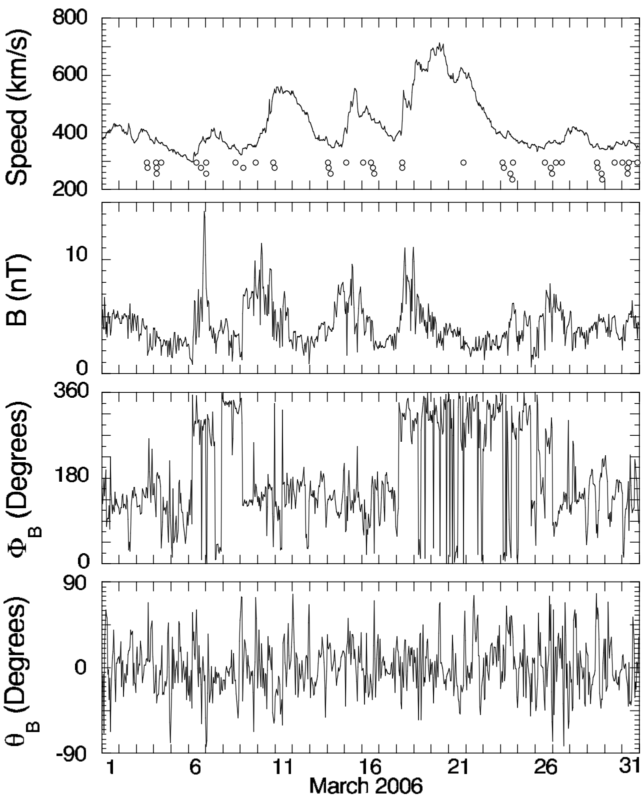

Figure 1. From top to bottom, 1-hr averages of solar wind speed, magnetic field strength, and the azimuth (Φ_B) and latitude (Θ_B) angles of the heliospheric magnetic field in March 2006, obtained from the OMNI solar wind database available on the cdaweb. Open circles beneath the speed profile in the top panel indicate times of Wind encounters with reconnection exhausts.

first exhaust, beginning at 07:42:45 UT, was swept past the spacecraft by the solar wind flow in ∼18 seconds and thus had a maximum local width of ∼6.9 × 10^3 km, (48 ion inertial lengths). The second exhaust, beginning at 07:51:14 UT, was swept past the spacecraft in ∼261 seconds and thus had a maximum local width of ∼1.0 × 10^5 km. In both events the jetting plasma was confined to a region where the field orientation changed. Those changes in orientation occurred in two distinct, but unequal, steps, with the field lingering at an intermediate orientation in between; that is, both events were associated with bifurcated current sheets. The total changes in field orientation across the exhausts were 30° and 74°, respectively. For a field shear angle of 180° one expects the change in $|\boldsymbol{V}|$ from outside to inside an exhaust to be comparable to the external Alfvén speed. In the case of the events in Figure 2, the changes in $|\boldsymbol{V}|$ were substantially less than the external Alfvén speeds owing to the relatively small local field shear angles. The so-called Walen test [*Hudson*, 1970] predicts $|\Delta \boldsymbol{V}|$ of the order of 15 km/s for the first event and 20 km/s for the second, consistent with what was measured.

[6] The two exhausts shown in Figure 2 occurred at interfaces separating different plasma and field states (this is clearer for the second event than for the first). In the first event, the transitions from outside to inside the exhaust on both the leading and trailing edges were slow-mode-like (increases in proton number density and temperature and decreases in $|\boldsymbol{B}|$), but this was not the case for the second event since the proton number density within that exhaust was intermediate to the densities external to the exhaust. The external proton beta (not shown) was ≪1 for both events.

[7] We have identified a total of 46 reconnection exhausts in the March 2006 interval. All of these exhausts were characterized by correlated changes in $\boldsymbol{V}$ and $\boldsymbol{B}$ at one edge and anti-correlated changes in $\boldsymbol{V}$ and $\boldsymbol{B}$ at the other edge. Many of the narrower exhausts lacked either a clear decrease in $|\boldsymbol{B}|$ or a clear increase in proton density or proton

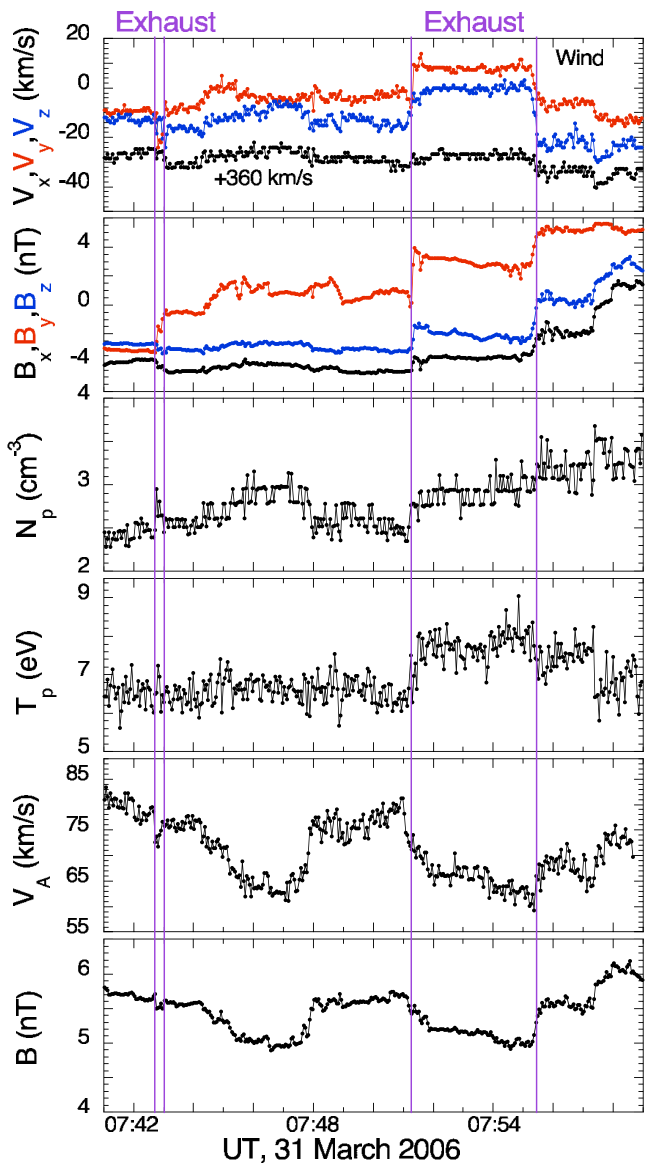

Figure 2. Selected solar wind plasma and magnetic field data from Wind in GSE coordinates for an 18-minute interval on 31 March 2006. From top to bottom the parameters shown are the components of $\boldsymbol{V}$, the components of $\boldsymbol{B}$, the proton density, the proton temperature, the Alfvén speed and $|\boldsymbol{B}|$. Vertical lines bracket two reconnection exhausts.

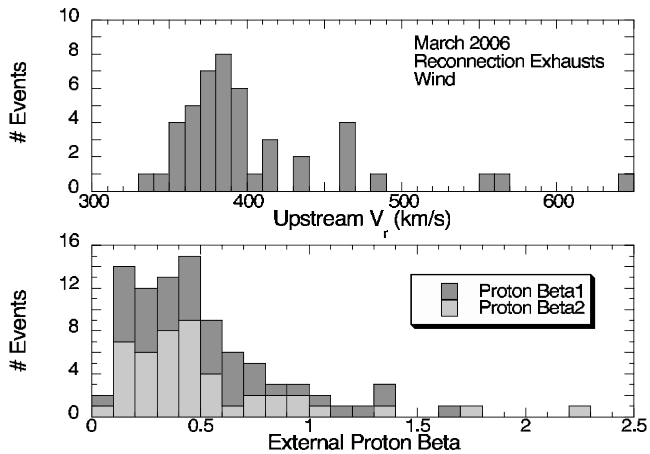

Figure 3. (top) Histogram of the radial component of the solar wind velocity immediately upstream from the exhausts in the March 2006 interval. (bottom) The proton beta immediately before (1) and after (2) the exhausts were encountered.

temperature, or some combination thereof; only 37 out of the 92 exhaust boundary transitions were slow-mode-like.

[8] The top panel of Figure 1 shows where the exhausts were encountered both in time and relative to solar wind stream structure. All but one of the events were observed in relatively low-speed solar wind; the event on 21 March was the first one we have identified in the high-speed (>600 km/s) wind from a coronal hole in any of the solar wind data sets (ACE, Wind, Ulysses, Helios 1 and 2) that we have examined in detail. A few of the exhausts were observed at times of increasing solar wind speed; however, the majority of the events were observed at times of decreasing or nearly constant wind speed. There was no obvious correlation between exhaust occurrence and $|\mathbf{B}|$. Although not obvious in Figure 1, none of the March 2006 exhausts occurred at the HCS and none were associated with ICMEs (since no ICMEs were encountered in the March 2006 interval). As for the events shown in Figure 2, the exhausts were usually associated with bifurcated (double step) current sheets, although in some cases one or the other of the field rotations at the exhaust edges were not sharply defined. In addition, the exhausts largely occurred at interfaces separating plasmas with somewhat different temperatures, densities, or field strengths.

[9] Figure 3 shows selected histograms of solar wind conditions immediately external to the exhausts. Similar to previous studies, the histograms demonstrate that the large fraction of the exhausts were embedded within solar wind having radial flow <400 km/s and proton beta <1.

[10] The second event shown in Figure 2 was the broadest exhaust observed in the March 2006 interval; however, its local width was smaller than the average width ($\sim 2.5 \times 10^5$ km) of solar wind exhausts previously discussed in the literature [e.g., *Gosling et al.*, 2005]. In contrast, the first exhaust shown in Figure 2 was quite narrow and the associated field shear angle was the second smallest yet observed. Figure 4 demonstrates that most (89%) of the exhausts observed in March 2006 had local widths $< 4 \times 10^4$ km (corresponding to exhaust crossing times $< \sim 100$ s). We have identified exhausts with widths down to about the limit of what can be resolved by the Wind 3-s plasma measurement; high resolution (92 ms) magnetic field data reveals that an exhaust encountered at 20:17:50 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 ion inertial lengths. The field shear angle for that event was 46°.

[11] Remarkably, 70% of the March 2006 exhausts were associated with field shear angles <90° and 13% were associated with field shear angles <40°. At exhaust widths $< 4 \times 10^4$ km there is only a weak correlation between field shear angle and exhaust width evident in Figure 4; however, exhausts with local widths $> 4 \times 10^4$ km accounted for all but one of the events associated with local field shear angles >145°.

3. Discussion

[12] During a randomly chosen month (March 2006) near the minimum of the 11-year solar activity cycle Wind encountered reconnection exhausts at an average rate of ~ 1.5 events/day, with the rate being considerably higher than that in the low-speed wind and considerably lower than that in the high-speed wind from coronal holes. A preliminary study reveals comparable or higher exhaust encounter rates by Wind during March and April 2007, also near solar activity minimum. This clearly indicates that magnetic reconnection occurs far more frequently (by a factor of ~ 36 in March 2006) in the solar wind than has been recognized to this point. None of the March 2006 events occurred at the HCS. We have previously noted that reconnection in the solar wind appears to be disproportionately associated with ICMEs [e.g., *Gosling et al.*, 2005, 2007b]. As none of the March 2006 reconnection exhausts were associated with ICMEs, that conclusion would appear to pertain only to the wider exhausts, which are largely associated with local magnetic shear angles considerably >90°.

[13] Perhaps surprisingly, this study demonstrates that reconnection exhausts in the solar wind are found most frequently at local field shear angles <90° and often at very small field shear angles. For example, a 21 s-wide exhaust encountered by Wind at 04:21:50 UT on 24 March 2006

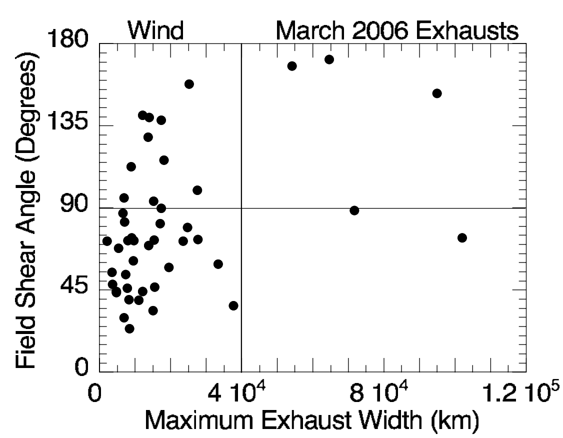

Figure 4. Scatter plot of magnetic field shear angle versus maximum local exhaust width for the March 2006 reconnection exhausts.

was associated with a field shear angle of only 24°. Thus, assuming that the local field shear angle is comparable to that at the x-line, reconnection in the solar wind occurs most often at locations where the so-called guide field component considerably exceeds the anti-parallel components. We suggest that the explanation for this is as follows. (1) When the field strengths on the opposite sides of a thin current sheet are comparable (as is usually the case in the solar wind), reconnection is geometrically possible for a wide range of field shear angles, including very small shear angles [*Sonnerup*, 1974]; and (2) the solar wind usually contains numerous current sheets, most of which are associated with relatively small field shear angles (see, for example, Figure 1).

[14] The time required for an exhaust to be convected past a spacecraft depends on the solar wind ***V***, the orientation of the exhaust relative to ***V***, and the local exhaust width. The latter, in turn, depends upon distance from the reconnection site and the exhaust wedge angle at the reconnection site, which scales directly as the dimensionless reconnection rate [e.g., *Petschek*, 1964]. A large fraction of the reconnection exhausts present in the solar wind in March 2006 had local widths $<4 \times 10^4$ km, corresponding to encounter times $<\sim 100$ s. These small widths are directly related to the fact that the field shear angles associated with reconnection in the solar wind are often relatively small. According to an analysis by *Sonnerup* [1974], the reconnection rate should scale as $v_{Ao}B_o\sin^2\alpha$, where B_o is the weaker of the fields abutting the current sheet, v_{Ao} is the Alfvén speed based on B_o, and α is the angle between B_o and the reconnection x-line (or equivalently, the guide field). For fields of equal strength abutting the current sheet, $\alpha = \theta/2$, where θ is the angle between the fields on opposite sides (i.e., θ is the shear angle). For equal field strengths and plasma densities on opposite sides of the exhaust, both the reconnection rate and the exhaust wedge angle should decrease as $\sin^2(\theta/2)$. Since the large majority of solar wind reconnection events are associated with small field shear angles, and thus relatively low reconnection rates, most solar wind reconnection exhausts are relatively narrow.

[15] Owing to the large fraction of solar wind exhausts that have narrow widths, a relatively high measurement cadence is required to resolve the majority of events. This explains why considerably fewer exhausts have been identified in other solar wind data sets where the plasma measurement cadences typically are $\sim$1 or 2 minutes. For example, with 64-s temporal resolution the ACE plasma experiment was able to resolve only two of the March 2006 events (however, ACE encountered only three of the current sheets associated with the broadest five events in the Wind data).

[16] Linear dimensions transverse to the radial direction increase directly with heliocentric distance in the spherically expanding solar wind. Thus, the fact that most reconnection exhaust widths in the solar wind are $<4 \times 10^4$ km indicates that the exhausts largely originate from local reconnection in the solar wind rather than from reconnection close to the Sun.

[17] There have been suggestions [e.g., *Matthaeus et al.*, 2003] that turbulence should commonly drive reconnection in the solar wind, and evidence for turbulence-driven reconnection has recently been reported in the shocked solar wind downstream from Earth's quasi-parallel bow shock [*Retino et al.*, 2007]. However, in the solar wind, turbulence is usually most pronounced at high wind speeds, where reconnection exhausts of the type discussed in this paper appear to be relatively rare (although a preliminary study of the Wind 3-s data in other months has led to the identification of a few additional exhausts in the high-speed wind). Further study is required to determine how frequently turbulence-driven reconnection exhausts occur in the high-speed solar wind.

[18] Finally, the energy associated with the jetting plasma within a reconnection exhaust ultimately will contribute to heating of the solar wind plasma with increasing heliocentric distance. However, as most of the exhausts are quite small, are associated with relatively low reconnection rates and low jetting speeds, and taken together occupy a relatively small volume of the solar wind, we do not expect that they contribute significantly to the overall heating of the solar wind with increasing heliocentric distance.

[19] **Acknowledgments.** We thank J. King, R. Lepping, and the cdaweb for making available data used in this study. Work at the University of Colorado has been supported by NASA grant NNG06GC27G and the NASA TR&T and STEREO programs.

References

Davis, M. S., T. D. Phan, J. T. Gosling, and R. M. Skoug (2006), Detection of oppositely directed reconnection jets in a solar wind current sheet, *Geophys. Res. Lett.*, *33*, L19102, doi:10.1029/2006GL026735.

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

Gosling, J. T., et al. (2006a), Petschek-type reconnection exhausts in the solar wind well beyond 1 AU: Ulysses, *Astrophys. J.*, *644*, 613.

Gosling, J. T., S. Eriksson, and R. Schwenn (2006b), Petschek-type magnetic reconnection exhausts in the solar wind well inside 1 AU: Helios, *J. Geophys. Res.*, *111*, A10102, doi:10.1029/2006JA011863.

Gosling, J. T., S. Eriksson, T. D. Phan, D. E. Larson, R. M. Skoug, and D. J. McComas (2007a), Direct evidence for prolonged magnetic reconnection at a continuous x-line within the heliospheric current sheet, *Geophys. Res. Lett.*, *34*, L06102, doi:10.1029/2006GL029033.

Gosling, J. T., S. Eriksson, D. J. McComas, T. D. Phan, and R. M. Skoug (2007b), Multiple magnetic reconnection sites associated with a coronal mass ejection in the solar wind, *J. Geophys. Res.*, doi:10.1029/2007JA012418, in press.

Hudson, P. D. (1970), Discontinuities in an anisotropic plasma and their identification in the solar wind, *Planet. Space Sci.*, *18*, 1611.

Huttunen, K. E. J., S. D. Bale, T. D. Phan, M. Davis, and J. T. Gosling (2007), Wind/WAVES observations of high-frequency plasma waves in solar wind reconnection exhausts, *J. Geophys. Res.*, *112*, A01102, doi:10.1029/2006JA011836.

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

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

Matthaeus, W. H., et al. (2003) Turbulent dissipation in the solar wind and corona, in *Solar Wind 10*, *AIP Conf. Proc.*, vol. 679, edited by M. Velli, R. Bruno, and F. Malara, pp. 427–432, Am. Inst. of Phys., Melville, N. Y.

Petschek, H. E. (1964), Magnetic annihilation, *NASA Spec. Publ. SP*, *50*, 425.

Phan, T. D., et al. (2006), A magnetic x-line extending more than 390 Earth radii in the solar wind, *Nature*, *439*, 175.

Retino, A., et al. (2007), In situ evidence of magnetic reconnection in turbulent plasma, *Nature Phys.*, *3*, 236, doi:10.1038/nphys574.

Sonnerup, B. U. O. (1974), Magnetopause reconnection rate, *J. Geophys. Res.*, *79*, 1546.

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

R. P. Lin and T. D. Phan, Space Sciences Laboratory, University of California, Berkeley, 7 Gauss Way, Berkeley, CA 94720, USA.

A. Szabo, NASA Goddard Space Flight Center, Code 696, Greenbelt, MD 20771, USA.