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THE DEPENDENCE OF MAGNETIC RECONNECTION ON PLASMA β AND MAGNETIC SHEAR: EVIDENCE FROM SOLAR WIND OBSERVATIONS

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ABSTRACT

We address the conditions for the onset of magnetic reconnection based on a survey of 197 reconnection events in solar wind current sheets observed by the *Wind* spacecraft. We report the first observational evidence for the dependence of the occurrence of reconnection on a combination of the magnetic field shear angle, θ, across the current sheet and the difference in the plasma β values on the two sides of the current sheet, $\Delta\beta$. For low $\Delta\beta$, reconnection occurred for both low and high magnetic shears, whereas only large magnetic shear events were observed for large $\Delta\beta$: Events with shears as low as 11° were observed for $\Delta\beta < 0.1$, but for $\Delta\beta > 1.5$ only events with $\theta > 100°$ were detected. Our observations are in quantitative agreement with a theoretical prediction that reconnection is suppressed in high β plasmas at low magnetic shears due to super-Alfvénic drift of the X-line caused by plasma pressure gradients across the current sheet. The magnetic shear-$\Delta\beta$ dependence could account for the high occurrence rate of reconnection observed in current sheets embedded within interplanetary coronal mass ejections, compared to those in the ambient solar wind. It would also suggest that reconnection could occur at a substantially higher rate in solar wind current sheets closer to the Sun than at 1 AU and thus may play an important role in the generation and heating of the solar wind.

Key words: magnetic fields – magnetic reconnection – plasmas – solar wind

1. INTRODUCTION

Magnetic reconnection in a current sheet is a universal plasma process that converts magnetic energy into particle energy, and is important in many space and laboratory contexts. While much is known observationally about the structure and dynamics of reconnection when reconnection is already ongoing, less is known about conditions necessary for the onset of reconnection. In situ spacecraft observations reveal that reconnection occurs in only a fraction of current sheets detected in the Earth's magnetosphere and in the solar wind. For example, the occurrence rate of reconnection in the Earth's magnetotail (associated with auroral substorms) is less than 5% (e.g., Angelopoulos et al. 1994), while reconnection signatures are seen in an equally small fraction of all solar wind current sheets at 1 AU (Gosling et al. 2005, 2007b). Observations in the magnetotail revealed that a key requirement for collisionless reconnection is the presence of thin current sheets, with the onset of reconnection occurring only when the thickness of a magnetotail current sheet is of the order of an ion skin depth or smaller (e.g., Sanny et al. 1994). However, Earth's dayside magnetopause is usually a thin current sheet due to the constant compression of the solar wind against the magnetosphere, but the reconnection occurrence rate is no more than 50% even when the magnetic shear angle (θ, the acute angle between the fields on opposite sides of a current sheet) across the magnetopause is large (>60°; e.g., Paschmann et al. 1986; Phan et al. 1996). This indicates that a thin current sheet is a necessary but not sufficient condition for reconnection. The magnetopause observations suggest that the plasma β (the ratio of plasma to magnetic pressure) in the magnetosheath region adjacent to the magnetopause may be a controlling factor, with reconnection more likely to occur when $\beta \ll 2$ (e.g., Paschmann et al. 1986; Trenchi et al. 2008). Furthermore, Scurry et al. (1994) reported that low magnetic shear reconnection events at the magnetopause were detected only when the magnetosheath β was low. However, no physical explanations for the dependence of reconnection on β were given in those studies.

Based on their simulations of reconnection with highly asymmetric density on the two sides of a current sheet similar to the magnetopause or expected at the heliopause, Swisdak et al. (2003, 2010) proposed that the occurrence of reconnection depend not on β alone, but on a combination of the difference in β on the two sides of the current sheet and the magnetic shear across the current sheet. The underlying physics is the diamagnetic drift of the X-line associated with the plasma pressure gradient across the current sheet. Reconnection is suppressed if the X-line drift speed (along the reconnection outflow direction) exceeds the reconnection outflow speed, in which case the reconnection outflow jet does not couple to the X-line. For a given magnetic shear θ across the current sheet, Swisdak et al. (2010) predicted that reconnection is allowed (suppressed) if $\Delta\beta$ satisfies (does not satisfy) the following relation:

$$\Delta\beta < 2(L/\lambda_i)\tan(\theta/2), \tag{1}$$

where L/λ_i is the width of the density gradient layer across the current sheet in units of the ion skin depth λ_i. This width is a free parameter but is expected to be comparable to the width of the ion diffusion region which, in turn, is expected to be of the order of λ_i. According to this prediction, reconnection is allowed for a large range of magnetic shears at low $\Delta\beta$ but requires a large magnetic shear at high $\Delta\beta$ values. This dependence of

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reconnection on $\Delta\beta$ and the magnetic shear is expected to be a universal reconnection onset condition which, in principle, can be used to predict when and where reconnection can or cannot occur in space and laboratory plasmas. However, its validity has never been quantitatively verified experimentally. In this Letter, we report the results of a comprehensive survey of β and magnetic shear conditions associated with solar wind reconnection events identified using observations from the *Wind* spacecraft. Solar wind events are ideal for this study because they often have well-defined and stable boundary conditions and are rapidly convected past a spacecraft by the solar wind flow (e.g., Gosling et al. 2005). Furthermore, the asymmetries between the boundary conditions on the two sides of the current sheets are generally smaller than those at the magnetopause, making it possible to distinguish between $\Delta\beta$ versus β effects. We find an excellent agreement between the observations and theory, with almost all identified reconnection events being in the regime where the diamagnetic drift effect should not suppress reconnection.

2. WIND INSTRUMENTATION

This study uses 3 s magnetic field data and 3 s resolution proton moments calculated onboard as well as electron temperatures computed on the ground from 3 s snapshots of three-dimensional electron distributions that were transmitted every 100 s.

3. EXAMPLE

To investigate the dependence of reconnection on magnetic shear and plasma β, one simply needs to identify reconnection events in solar wind current sheets and to measure the total β (effectively $\beta_{\mathrm{proton}}+\beta_{\mathrm{electron}}$) in the two inflow regions as well as the total magnetic shear across the entire current sheet. In this section, we show an example to illustrate the identification of a reconnection event and its boundary conditions.

Figure 1 shows the 2002 April 10 event where the *Wind* spacecraft detected the passage of a solar wind current sheet (panel (b)) with embedded reconnection outflow (panel (c)) at 15:49:20–15:50:05 UT (between the second and third vertical dashed lines). The magnetic shear (θ) across the entire exhaust was $\sim 60°$. The sharp changes in the magnetic field orientation near the two edges and a plateau in between indicate that the current sheet was bifurcated (e.g., Phan et al. 2006; Gosling & Szabo 2008). The reconnection exhaust was identified by the presence of nearly Alfvénic accelerated flow (panel (c)) within the region where the field rotated, with the change in **V** (panel (c)) and **B** (panel (b)) being anti-correlated on the leading edge and correlated on the trailing edge of the exhaust, consistent with Alfvénic disturbances propagating in opposite directions along reconnected field lines away from the reconnection site (e.g., Gosling et al. 2005). The observed changes in the flow speed were ~ 30 km s^{-1} and ~ 22 km s^{-1} across the leading and trailing edges of the exhaust, respectively, and these changes were $\sim 87\%$ and 91% of the predicted changes at the corresponding edges of the exhaust according to the rotational discontinuity jump condition (Hudson 1970):

$$\mathbf{V_2} - \mathbf{V_1} \sim \pm(\mathbf{B_2} - \mathbf{B_1})/(\mu_0\rho_1)^{1/2}, \tag{2}$$

where **V**, **B**, and ρ are the proton bulk velocity, magnetic field, and proton mass density, respectively. Subscripts 1 and 2 denote the inflow and outflow regions, respectively. The positive and negative signs of this relation refer to the trailing and leading edges of the exhaust, respectively, for this example. The pressure anisotropy effect was omitted for simplicity.

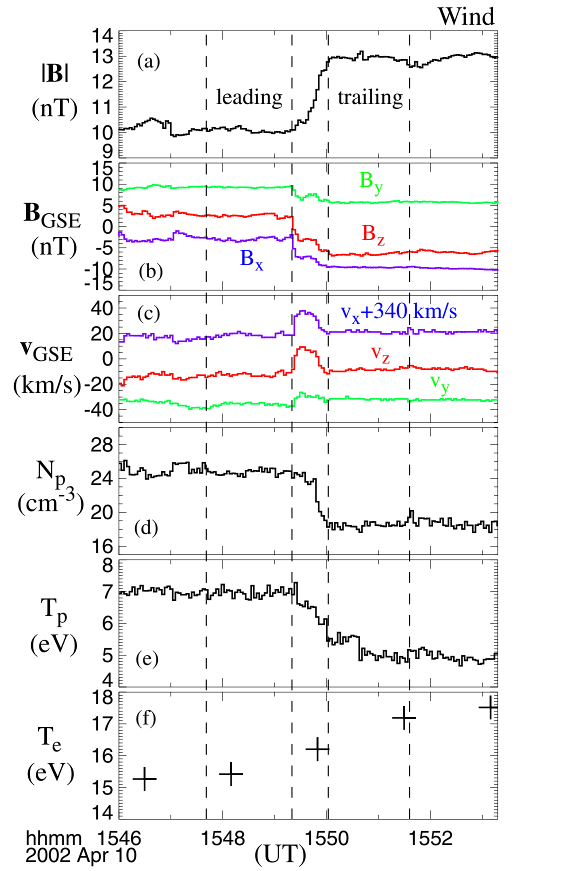

Figure 1. Detection of a reconnection exhaust by the *Wind* spacecraft located at GSE [34, 151, 3] Earth radii on 2002 April 10. In the geocentric solar ecliptic (GSE) coordinate system, the +*x*-direction points from the Earth to the Sun, the +*z*-direction is perpendicular to the ecliptic plane and northward, and +*y* completes the right-handed orthogonal system. (a) The magnetic field magnitude, (b) the magnetic field components in GSE coordinates, (c) the proton flow velocity components in GSE, (d) the proton number density, (e) the proton temperature, and (f) the electron temperature. The interval between the left (right) pair of vertical dashed lines defines the boundary condition for the leading (trailing) side of the exhaust.

The β values of the two inflow regions were obtained by averaging β over the intervals between the left and right pairs of vertical dashed lines shown in Figure 1 on the two sides of the exhaust. These rather long (>90 s) intervals were chosen such that they contained at least one electron temperature measurement. The plasma and field conditions were relatively stable in these intervals. The average inflow β was 2.19 on the leading edge side and 0.99 on the trailing edge side. With a β difference ($\Delta\beta$) of 1.2 and a magnetic shear of 60°, this event is within the predicted regime in which reconnection is not suppressed by the diamagnetic effect if $L \sim \lambda_i$ (see Relation 1).

Finally, we note that although many previously reported solar wind reconnection events had proton density and temperature enhancements and magnetic field magnitude depressions in the exhausts (compared with values outside; e.g., Gosling et al. 2005), there were no density (panel (d)) and temperature (panel (e)) enhancements or field depression (panel (a)) in this event. Instead, the density, temperature, and field strength within the exhaust were intermediate between their values on the two

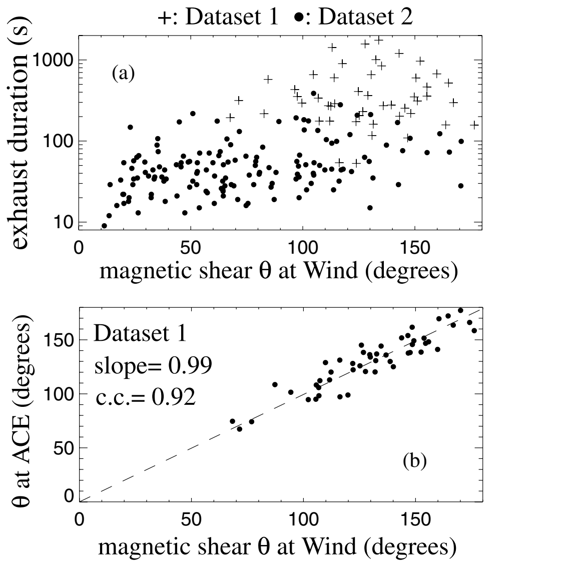

Figure 2. (a) Scatter plot of exhaust crossing durations vs. magnetic shear for 197 reconnection exhausts detected by *Wind*. "+" denotes Dataset 1 and dots denote Dataset 2. (b) Scatter plot of the magnetic shear across the exhaust observed at *ACE* vs. the shear observed at *Wind* for Dataset 1.

sides of the exhaust. The absence of an exhaust density or temperature enhancement and/or field depression is typical for events with highly asymmetric plasma conditions (e.g., Gosling et al. 2007b).

4. STATISTICAL SURVEY

4.1. Data Set and Selection Criteria

We searched for reconnection exhausts in the solar wind using *Wind* data. We combined a previously published data set of 50 large-scale reconnection events seen by two spacecraft (*Wind* and *ACE*) from 1997 to 2005 (termed "Dataset 1"; Phan et al. 2009), with a new set of 147 additional reconnection events observed by *Wind* in the year 2002 alone (termed "Dataset 2"). There are several differences between the two data sets in terms of their selection criteria. In Dataset 1, we required, in addition to the presence of roughly Alfvénic outflows, that (1) the current sheet crossing duration at *ACE* be >64 s in order for the *ACE* plasma instrument to detect the outflow jet and that (2) the ion density and temperature be enhanced within the exhaust. While the long crossing duration was required for the two-spacecraft investigation of large-scale reconnection, it had the adverse effect of excluding the very common narrow exhaust events often associated with small magnetic shears (Gosling et al. 2007b; Gosling & Szabo 2008), thus the smallest magnetic shear of the 50 events in Dataset 1 was 67° (Figure 2(a)). The requirement of density and temperature enhancements further excluded most exhausts with large density or temperature asymmetry on the two sides of the current sheet similar to the example in Section 3.

For the new survey of *Wind* observations in 2002, we identified the reconnection exhausts solely on the presence of roughly Alfvénic accelerated flows bounded on one side of the exhaust by correlated changes in **V** and **B** and anti-correlated changes in **V** and **B** on the other side. One further requirement was that the plasma and field parameters had to be stable in the inflow region long enough (∼100 s) to include at least one electron temperature measurement in the inflow interval for the β determination. With these much less restrictive criteria, 147 exhausts (excluding 2 events that overlapped with Dataset 1) were identified in 2002 alone. It should be pointed out that even though our initial identification of the exhausts based on the presence of accelerated flows was qualitative, the agreement between the observed flow acceleration and that predicted by the rotational discontinuity jump condition (Relation 2 above) was better than 50% in all but two of the 197 events, with an average agreement of 81%.

The exhaust crossing durations and the magnetic shears for Datasets 1 and 2 are shown as a scatter plot in Figure 2(a). As expected, the majority (92%) of the events in Dataset 2 have short (<120 s) duration, as opposed to Dataset 1 in which only 8% of the events had duration <120 s. Panel (a) also shows that Dataset 2 added a large number of low magnetic shear events to the study, with the smallest shear at 11°. The large abundance of low-shear events is similar to that previously reported by Gosling et al. (2007b) and simply reflects the fact that low magnetic shear current sheets are the rule in the solar wind.

Strictly speaking, the comparison between the spacecraft observations and the theoretical prediction (Relation 1) is meaningful only if the local magnetic shear (at the spacecraft) is similar to the shear at the X-line. Figure 2(b) shows a comparison between the magnetic shear, θ, measured at *ACE* and *Wind* in Dataset 1. There is a good agreement between the θ at the two spacecraft even though the spacecraft were often tens of thousands of ion skin depths (10^5–10^6 km) apart. The average difference in θ at the two spacecraft was ∼8° in Dataset 1, with the largest difference being 21°. In addition, most solar wind reconnecting current sheets are approximately planar (e.g., Phan et al. 2009) on the scales of tens to hundreds of Earth radii. Together, these findings suggest that the local magnetic shear is usually comparable to that at the X-line even though in most solar wind reconnection events the spacecraft crossings of the exhausts take place far (hundreds or thousands of ion skin depths) away from the X-line (e.g., Phan et al. 2006; Davis et al. 2006; Gosling et al. 2007c).

We now proceed with the survey of the dependence of the occurrence of solar wind reconnection events on β and magnetic shear based on the conditions at the spacecraft crossing of the exhausts.

4.2. Results

Figure 3(a) shows a scatter plot of the magnetic shear and $\Delta\beta$ for all 197 reconnection events. At low $\Delta\beta$ reconnection exhausts were observed for a large range of magnetic shears, whereas only large-shear events were observed at high $\Delta\beta$. For example, events with shears as low as 11° (i.e., reconnection between nearly parallel magnetic fields) were observed for $\Delta\beta < 0.1$, but for $\Delta\beta > 1.5$ only events with $\theta > 100°$ were detected. Overlaid are theoretical curves from Relation 1 for three different values of the scale of the density gradient at the X-line: $L = 0.5\ \lambda_i$, $1.0\ \lambda_i$, and $2.0\ \lambda_i$. The theoretical curve that best confined the reconnection events is the one with $L = \lambda_i$. There were essentially no reconnection events observed in the regime below this curve, consistent with reconnection being suppressed in that regime. The fact that the $L = 1.0\ \lambda_i$ curve, not the $0.5\ \lambda_i$ curve, best describes the data seems reasonable since it is unlikely that the scale of the density gradient at the X-line is narrower than one ion skin depth.

We also examined the occurrence of reconnection events as a function of the magnetic shear and β, instead of $\Delta\beta$, to see whether the dependence on β fits the data equally well. However, Figure 3(b) shows that the data are less well ordered using β. The

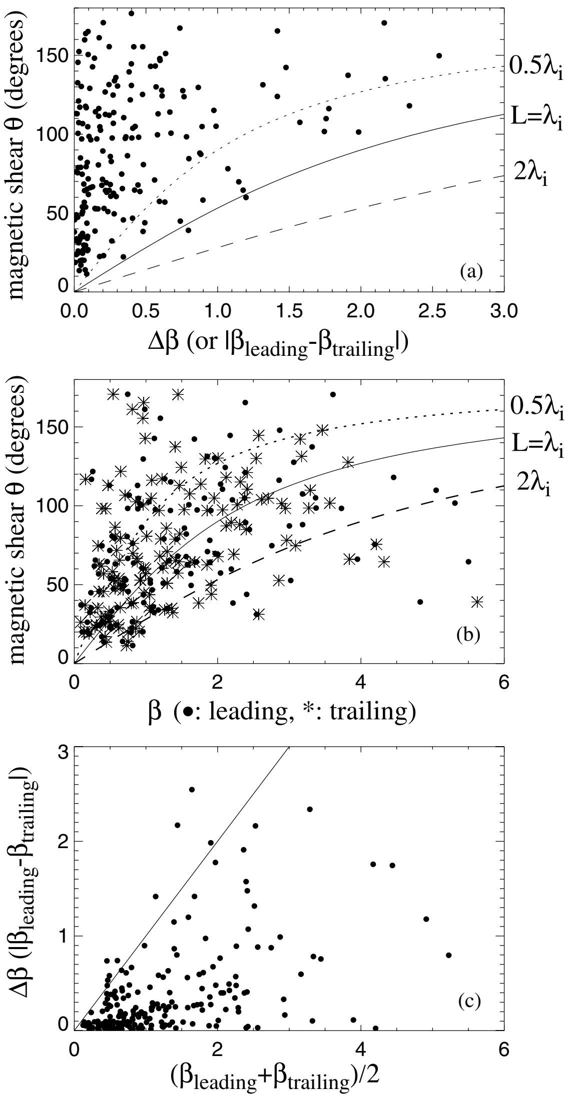

Figure 3. (a) Scatter plot of the exhaust magnetic shear vs. the difference of β on the two sides of the exhaust for all 197 reconnection events (Dataset 1 + Dataset 2) of the present study, (b) scatter plot of the magnetic shear angle as a function of β on the two sides of the exhaust (dots are the inflow β on the leading side and "*" are on the trailing side), (c) the difference of β vs. the average of β of the two sides of the exhaust. The three curves in panels (a) and (b) are the theoretical curves (Relation 1) for three values of the density gradient scales in units of the ion skin depth λ_i (Swisdak et al. 2010). The theory predicts the suppression of reconnection below these curves.

fact that the dependence is on $\Delta\beta$, not β, is consistent with reconnection being suppressed by the diamagnetic drift of the X-line associated with the pressure gradients across the current sheet (Swisdak et al. 2003, 2010).

Finally, Figure 3(c) shows that there is a link between β and $\Delta\beta$. When β is low on both sides, $\Delta\beta$ is necessarily small. However, $\Delta\beta$ is not necessarily large when β is high. This implies that reconnection can occur for almost any magnetic shear in low-β solar wind, regardless of the level of asymmetry in the boundary conditions.

5. DISCUSSIONS

Our survey of *Wind* data shows a clear dependence of the occurrence of solar wind reconnection on a combination of the magnetic shear and $\Delta\beta$, the difference in plasma β on the two sides of the current sheet. At low $\Delta\beta$ reconnection events are observed for a large range of the magnetic shears, with shear as low as 11° when $\Delta\beta < 0.1$. At higher $\Delta\beta$ only large shear events are observed: For $\Delta\beta > 1.5$ only events with $\theta > 100°$ were detected. Our finding is consistent with the prediction of Swisdak et al. (2010) that low-shear reconnection is suppressed at large $\Delta\beta$ due to the diamagnetic drift of the X-line associated with plasma pressure gradients across the current sheet. The quantitative agreement between the observations and theory is remarkable considering the fact that the observations are generally made far from the X-line whereas the conditions for the theoretical prediction pertain to the regions around the X-line.

It should be emphasized that we have only examined current sheets containing reconnection exhausts in this study. Thus, the results presented here only indicate that Relation 1 is a necessary condition for reconnection. This is clearly not a sufficient condition for reconnection. Other effects such as thick current sheets could suppress reconnection even in regimes where the diamagnetic drift effect permits reconnection. Nevertheless, the suppression of low-shear reconnection at high $\Delta\beta$ has important general consequences for the occurrence of reconnection in space and laboratory plasmas.

A possible implication of the magnetic shear–$\Delta\beta$ effect is that the occurrence rate of solar wind reconnection, especially of low magnetic shear reconnection, would be higher in current sheets that are embedded within or in front of interplanetary coronal mass ejections (ICMEs) compared to those in the ambient solar wind. This is because β tend to be much lower (and therefore smaller $\Delta\beta$) in ICMEs. Indeed, surveys of solar wind reconnection events reveal that a large fraction of the solar wind reconnection events that have been identified so far are associated with ICMEs (Gosling et al. 2007a; Gosling & Szabo 2008; Phan et al. 2009) even though the number of current sheets in ICMEs represents a small fraction of the total number of current sheets in the solar wind.

Similarly, one would expect a higher occurrence rate of solar wind reconnection closer to the Sun. At 1 AU reconnection is detected in a small fraction of solar wind current sheets encountered by spacecraft; thus, reconnection is not energetically important at 1AU in terms of the evolution of heliospheric plasmas and fields (e.g., Gosling 2007, 2010). However, the occurrence rate of solar wind reconnection could be much higher closer to the Sun because of the lower plasma β environment there. The expected average plasma β at 10 solar radii (Rs) is ~0.1 (thus $\Delta\beta < 0.1$ according to Figure 3(c)), or about a factor of 10 lower than at 1 AU. According to Relation 1, at $\Delta\beta < 0.1$ reconnection is permitted for shears as low as 5°. The NASA *Solar Probe* mission, with its closest approach to the Sun at 9.5 Rs, will reveal if solar wind reconnection occurs more frequently close to the Sun and what role it might play in the generation and heating of the solar wind.

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REFERENCES

Angelopoulos, V., et al. 1994, J. Geophys. Res., 99, 21257
Davis, M. S., Phan, T. D., Gosling, J. T., & Skoug, R. M. 2006, Geophys. Res. Lett., 33, L19102

Gosling, J. T. 2007, ApJ, 671, L73

Gosling, J. T. 2010, in AIP Conf. Proc. 1216, Twelfth International Solar Wind Conference, ed. M. Maksimovic et al. (Melville, NY: AIP), 188

Gosling, J. T., Eriksson, S., McComas, D. J., Phan, T. D., & Skoug, R. M. 2007a, J. Geophys. Res., 112, A08106

Gosling, J. T., Phan, T. D., Lin, R. P., & Szabo, A. 2007b, Geophys. Res. Lett., 34, L15110

Gosling, J. T., & Szabo, A. 2008, J. Geophys. Res., 113, A10103

Gosling, J. T., Skoug, R. M, McComas, D. J., & Smith, C. W. 2005, J. Geophys. Res., 110, A01107

Gosling, J. T., et al. 2007c, Geophys. Res. Lett., 34, L20108

Hudson, P. D. 1970, Planet. Space Sci., 18, 1611

Paschmann, G., Baumjohann, W., Sckopke, N., Papamastorakis, I., & Carlson, C. W. 1986, J. Geophys. Res., 91, 11099

Phan, T. D., Gosling, J. T., & Davis, M. 2009, Geophys. Res. Lett., 36, L09108

Phan, T. D., Paschmann, G., & Sonnerup, B. U. O. 1996, J. Geophys. Res., 101, 7817

Phan, T. D., et al. 2006, Nature, 439, 175

Sanny, J., McPherron, R. L., Russell, C. T., Baker, D. N., Pulkkinen, T. I., & Nishida, A. 1994, J. Geophys. Res., 99, 5805

Scurry, L. C., Russell, C. T., & Gosling, J. T. 1994, J. Geophys. Res., 99, 14811

Swisdak, M., Rogers, B. N., Drake, J. F., & Shay, M. A. 2003, J. Geophys. Res., 108, 1218

Swisdak, M., Opher, M., Drake, J. F., & Alouani Bibi, F. 2010, ApJ, 710, 1769

Trenchi, L., et al. 2008, J. Geophys. Res., 113, A07S10