Statistical properties of solar wind reconnection exhausts

R. Mistry1, J. P. Eastwood1, T. D. Phan2, and H. Hietala3

1The Blackett Laboratory, Imperial College London, London, UK, 2Space Sciences Laboratory, University of California, Berkeley, California, USA, 3Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California, USA

Abstract The solar wind provides an excellent opportunity to study the exhausts that form as a result of symmetric guide field reconnection, where spacecraft rapidly cross the exhausts far downstream of the X line. We study the statistical properties of solar wind exhausts through a superposed epoch analysis of 188 events observed at 1 AU using the Wind spacecraft. These events span a range of guide fields of 0 to 10 times the reconnecting magnetic field and inflow region plasma beta of 0.1 to 6.6. This analysis reveals that the out-of-plane magnetic field is enhanced within solar wind exhausts. Furthermore, the amount by which the plasma density and ion temperature increase from inflow region to exhaust region is found to be a function of the inflow region plasma beta and reconnection guide field, which explains the lack of these enhancements in a subset of previous observations. This dependence is consistent with the scaling of ion heating with inflow region Alfvén speed, which is measured to be consistent with previous observations in the solar wind and at the magnetopause.

1. Introduction

The release of magnetic energy that occurs during magnetic reconnection is often realized in the form of accelerated and heated particles which form collimated exhausts. In the solar wind they can extend over thousands of ion inertial lengths (\(d_i\)) from the reconnection site [Davis et al., 2006; Mistry et al., 2015], and their boundaries are sites of further plasma energization. In situ observations of this far downstream of the reconnecting sites are crucial to understanding the exhausts that form as a result of reconnection, as these distances are far beyond the range of that that is typically modeled using simulations. The solar wind is an ideal environment in which to study these systems since the exhausts are generally two dimensional and planar [Phan et al., 2009]. Furthermore, despite the presence of plasma discontinuities in the solar wind [Borovsky, 2008; Horbury et al., 2001], plasma surrounding reconnection exhausts in the solar wind is relatively homogenous in contrast to earthward directed reconnection exhausts in the magnetotail, for example, which interact with the dense inner magnetosphere [e.g., Runov et al. [2011]].

Despite solar wind reconnection occurring with almost symmetric inflow conditions and forming exhausts which extend over large distances, observations show that there is considerable variability between different reconnection exhausts. Reconnection exhausts have been observed where the current layer is bifurcated [e.g., Gosling et al., 2005; Gosling et al., 2006b; Phan et al., 2006] as well as where the current has a single more broad layer [e.g., Gosling, 2007; Gosling et al., 2007b]. Multispacecraft observations indicate that this is affected by the distance downstream of the X line at which the exhaust is observed, with the current layer becoming bifurcated further downstream [Mistry et al., 2015]. Exhausts are often also observed with enhancements in density and temperature within the exhaust region [e.g., Gosling et al., 2005]; however, exhausts have been observed with the absence of such signatures [Gosling, 2007; Gosling et al., 2007a]. The reasons as to why these signatures differ from one exhaust to the next have not been fully explored, and these differences make it difficult to form an understanding of the general characteristics of solar wind exhausts.

Exhausts at large distances downstream of the diffusion region (where kinetic processes are dominant) are typically modeled using fluid theories [Vasyliunas, 1975]. In the Petschek [1964] model of symmetric reconnection with antiparallel magnetic fields, the exhaust is bound by MHD slow mode shocks. If the guide field (the ratio of the out-of-plane magnetic field to the reconnecting component of the field) is nonzero, however, rotational discontinuities are predicted to form upstream of the slow shocks [Y Lin and Lee, 1993, 1995]. More recent kinetic simulations have also shown the exhaust boundaries to resemble a series of anisotropic MHD discontinuities involving slow shocks and rotational discontinuities [Innocenti et al., 2015; Liu et al., 2012].

©2017. The Authors. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
In reality, the structure of reconnection exhausts in collisionless plasmas differs from idealized fluid descriptions. Hall magnetic field observations at several solar wind exhausts indicate that differential ion and electron motion persists thousands of ion inertial lengths downstream of the X line [Mistry et al., 2016]. Additionally, counterstreaming ion beams have been observed in the solar wind [Gosling et al., 2005], magnetosheath [Phan et al., 2007], magnetopause [Gosling et al., 1990], and magnetotail [Hoshino et al., 1998]. The increase in ion temperature associated with such beams is predicted to be 33% of the magnetic energy to each proton-electron pair [Drake et al., 2009]; however, observations in the solar wind [Drake et al., 2009] and at the magnetopause [Phan et al., 2014] place this fraction at 13%. These observations did not include very strong guide field events which are often observed in the solar wind [Phan et al., 2010], and an explanation for the discrepancy between the observed and predicted scalings has not yet emerged.

Here we study 188 exhausts observed by the Wind spacecraft using a superposed epoch analysis to determine their average properties and structure. These results show that the out-of-plane magnetic field is enhanced throughout the exhaust region, resembling simulations where the exhausts are found to be bound by rotational discontinuities. Furthermore, we show that the increase in density and ion temperature observed within solar wind exhausts is a function of the reconnection guide field and inflow region plasma beta. The scaling of the ion temperature increase with inflow region Alfvén speed is calculated for these events and is found to be consistent with previous measurements [Drake et al., 2009; Enél et al., 2014; Phan et al., 2014]. This indicates that ion temperature enhancements in solar wind exhausts are expected to be weak in the presence of significant guide fields.

2. Data Set

We first provide an overview of the data set used in this study. These events were observed by Wind at 1 AU and used by Phan et al. [2010] to demonstrate that solar wind reconnection events satisfy an onset condition for reconnection that is determined by the magnetic shear angle and the difference in plasma beta across the current sheet [Swisdak et al., 2010]. We use magnetic field data at 11 vectors/s [Lepping et al., 1995] and 3DP onboard ion moments at 3 s cadence [R P Lin et al., 1995]. Electron moments are calculated on the ground from distributions acquired using 3DP over 3 s and transmitted to ground every 100 s.

Phan et al. [2010] analyzed 197 events observed by Wind. These events were composed of a set of 50 exhausts that were observed by ACE and Wind between 1997 and 2004 and 147 exhausts that were observed by Wind in 2002. The primary criteria used to identify these events was the observation of a pair of roughly Alfvénic disturbances in the solar wind associated with a current sheet, such that changes in the magnetic field and ion velocity were correlated on one side of the current sheet and anticorrelated on the other side [see Gosling et al., 2005]. Further details of the selection criteria for the set of 50 and 147 events are provided in Phan et al. [2009] and Phan et al. [2010], respectively.

In their study of 197 events, Phan et al. [2010] were primarily concerned with the reconnection inflow conditions. Several of these events had magnetometer or 3DP ion data gaps within the exhaust region. These events were excluded from the analysis as the primary focus of the present study is the exhaust region itself. The remaining 188 events are used in this study and have been previously used to study Hall magnetic fields in solar wind exhausts [Mistry et al., 2016].

Three intervals (which are identical to those used in Phan et al. [2010]) were defined for each event. The exhaust interval is defined as the period over which the magnetic field vector varies (not just one component). Intervals preceding and following the exhaust (of between 21 s and 237 s) were defined as inflow regions 1 and 2, respectively, which were chosen to include at least one electron distribution measurement. Plasma and field measurements within inflow regions 1 and 2 were checked to ensure that they contained no discontinuities, large variations, or waves. Furthermore, measurements within inflow regions 1 and 2 were found to be stable (see later discussion on uncertainties of mean inflow region values). Average measurements from these inflow regions are therefore representative of the plasma immediately upstream of the exhaust boundaries, i.e., plasma flowing into the exhaust. These intervals are listed for each event in Table S1 in the supporting information.

Current sheet normal coordinates were found for each event by applying hybrid-minimum variance analysis (hybrid-MVA) [Gosling and Phan, 2013] to magnetic field data obtained during the exhaust intervals. The
The current sheet normal direction is \( \mathbf{N} = (\mathbf{B}_1 \times \mathbf{B}_2)/(|\mathbf{B}_1 \times \mathbf{B}_2|) \), where \( \mathbf{B}_1 \) and \( \mathbf{B}_2 \) are mean magnetic field vectors from inflow regions 1 and 2, respectively. The guide field direction is \( \mathbf{M} = (\mathbf{N} \times \mathbf{L}')/(|\mathbf{N} \times \mathbf{L}'|) \), where \( \mathbf{L}' \) is the maximum variance direction obtained from minimum variance analysis of the interval [Sonnerup and Cahill, 1967]. The exhaust outflow direction is \( \mathbf{L} = \mathbf{M} \times \mathbf{N} \). Hybrid-MVA is found to identify the current sheet normal direction more reliably than minimum variance analysis [Knetter et al., 2004]. Minimum variance analysis often fails to suitably separate the intermediate and minimum variance directions and consequently gives a normal magnetic field which is unrealistically large for a current sheet.

Figure 1a shows the durations over which the exhausts were measured (the exhaust interval). These span a range of 3.7 s to 1610 s, with a median of 42 s. This duration depends on the exhaust width in the normal direction, the solar wind speed, and the trajectory of the spacecraft relative to the exhaust. The exhaust width in the normal direction is measured using \( (V_{\text{sw}} \times \mathbf{N}) \Delta t \), where \( \Delta t \) is the exhaust interval duration and \( V_{\text{sw}} \) is the solar wind velocity (i.e., the mean velocity vector from inflow regions 1 and 2). These are shown in units of kilometer in Figure 1b and inflow region ion inertial length in Figure 1c (using the measured inflow region density; see Figure 2b). The median exhaust width is 120 \( d_i \). This corresponds to a measurement made 600

Figure 2. Mean values in the inflow region of (a) magnetic field magnitude, (b) ion density, (c) ion temperature, (d) electron temperature, and (f) total plasma beta. (g) \( X_{\text{GSE}} \) component of the solar wind speed. The vertical axis shows the number of events in each bin.
downstream of the reconnection X line, assuming a canonical normalized reconnection rate of 0.1, suggesting that exhausts in the solar wind are generally observed far downstream of the reconnection X line.

The means of measurements made in the two regions are used to calculate average inflow region values for each event. Distributions of the inflow region magnetic field magnitude, density, and ion and electron temperatures are shown in Figure 2. The electron temperature is slightly higher than that of the ions. The median total plasma beta is 0.9, with a range of 0.1–6.6.

These inflow region parameters are similar to solar wind parameters for the slow solar wind observed at 1 AU. Indeed, solar wind speed measurements show that reconnection exhausts are more frequently detected at low speeds (Figure 2f). This is consistent with previous studies that concluded that reconnection exhausts are less frequently detected in the fast solar wind [Gosling, 2007].

Figure 3 shows differences in the magnetic field magnitude, plasma density, ion temperature, and electron temperature between inflow regions 1 and 2, normalized by their mean. These differences are generally weak (<0.2), demonstrating that the vast majority of reconnection events in the solar wind at 1 AU may be considered to have essentially symmetric inflow conditions. Nevertheless, there are some events with sizable asymmetries, and so the inflow region Alfvén speed is determined using the asymmetric Alfvén speed [Cassak and Shay, 2007]. These speeds are shown in Figure 4a.

If $V_L$ differs on either side of the current sheet, this would imply that a flow shear exists across the current sheet. Figure 4b shows that these flow shears are small with respect to the inflow region Alfvén speed.
Flow shears across solar wind reconnection current sheets are therefore not expected to result in X line drifts that may significantly affect the reconnection process [Doss et al., 2015].

Finally, Figure 5 shows that these events have a rather uniform distribution of magnetic shear angles across the range 11°–173°, which are calculated using the mean magnetic field from inflow regions 1 and 2. These correspond to guide fields of 0–10, where the guide field $B_G$ is defined as the ratio of the out-of-plane magnetic field $B_M$ to the reconnection magnetic field $B_L$ in the inflow region, and is dimensionless.

### 3. Superposed Epoch Analysis

#### 3.1. Method

In this section we conduct a superposed epoch analysis in order to establish the average properties of solar wind reconnection exhausts. When comparing these events, the large degree of variability between current sheet and plasma parameters should be considered. As shown in Figure 2, the inflow region magnetic field, density, and temperature can vary significantly. This, as we shall see, is related to the large range of guide fields included in the data set.

Measurements made across relatively wide exhausts and relatively narrow exhausts may show variations on different temporal scales. In order to compare such events, the time axis is normalized for each event so that 0 and 1 correspond to measurements at the boundaries of the exhausts (i.e., the start and end of the exhaust intervals). Since the exhausts are frozen to the solar wind, time series measurements can be considered as measurements along a line antiparallel to the solar wind flow. We therefore treat the time axis simply as the normalized distance ($y$) through the reconnection exhaust. This normalization allows events with different durations to be directly compared.

Each parameter of interest is normalized using the mean values from inflow regions 1 and 2. Without such normalization in density, for example, the superposed data would include densities over the range 0.8–35.4 cm$^{-3}$, in which case underlying trends in changes in the density from the inflow region to exhaust region would be masked by the variability of inflow region densities.

Reconnection exhausts in the solar wind have arbitrary orientations. In order to compare events, consistent coordinate systems must be used. We define coordinate systems for each event so that the measured exhaust outflow is in the $+L$ direction and the guide field is in the $+M$ direction. Because these exhausts can have any orientation in the solar wind, the spacecraft may go from the side where $B_L$ is positive to the side where it is negative, or from the negative side to the positive side. Time series measurements are therefore reversed in time if $B_L$ changes from negative to positive. In this way, all measurements in the superposed epoch analysis are such that $B_L > 0$ is measured at $y = 0$ and $B_L < 0$ is measured at $y = 1$. This system has the caveat that the field line geometry could be such that $B_N$ is expected to be either positive or negative, depending on whether the time series measurements were reversed.

Figure 5. (a) Reconnection guide field (inflow region $B_M/B_L$) and (b) magnetic shear angle. The vertical axis shows the number of events in each bin.
3.2. Results

Figure 6 shows the results of a superposed epoch analysis of the 188 solar wind reconnection exhausts. Individual event measurements are shown in grey, mean values in blue, and the ±1 standard deviation range is shown in orange. The thickness of the blue line indicates the ±1 standard deviation range of the mean value (i.e., $\sigma_{{mn}}$, where $n$ is the number of events).

Figures 6a–6c show magnetic field measurements normalized by the mean value of $|B_1|$ measured in inflow regions 1 and 2 ($B_{L,1n}$). The out-of-plane field shown is the measured field ($B_m$) minus the mean inflow region out-of-plane field ($B_{M,1n}$), normalized by $B_{L,1n}$, i.e., $(B_m - B_{M,1n})/B_{L,1n}$. Figures 6d–6f show ion velocity measurements with mean measurements from the inflow regions subtracted (which is equivalent to a transformation from the spacecraft frame of reference to the reconnection exhaust frame of reference), normalized by the asymmetric inflow region Alfven speed, $C_{AS}$ [Cassak and Shay, 2007], which is defined as

$$
C_{AS}^2 = \frac{B_{L,1} B_{L,2}}{\mu_0} \frac{(B_{L,1} + B_{L,2})}{(\rho_1 B_{L,2} + \rho_2 B_{L,1})},
$$

Figure 6. Superposed epoch analysis of 188 events. Individual events are shown in grey. The standard deviation of the measurements are shown in orange, and the mean values are shown in blue, where the width of the line is the ±1 standard deviation range of the mean value.
where \( \rho \) is the plasma density and subscripts 1 and 2 refer to mean values from inflow regions 1 and 2, respectively. Magnetic field magnitude, ion density, and ion temperature measurements, normalized by their respective mean values in the inflow regions, are shown in Figures 6g–6i.

The thermal (ion + electron) pressure, normalized by its inflow region value, is shown in Figure 6j. As previously noted, inflow regions 1 and 2 contain at least one electron temperature measurement. For most events, however, measurements of the electron temperature within the exhaust are not available. The electron contribution to the thermal pressure is calculated by linearly interpolating the electron temperature between \( y = 0 \) and \( y = 1 \) and by considering the electron temperature for \( y < 0 \) and \( y > 1 \) to be the value used in that inflow region. The magnetic pressure and total pressure are shown in Figures 6k and 6l, respectively, each normalized by their mean inflow region values. The total pressure is calculated using magnetic field data averaged to the 3 s ion moments and the linearly interpolated electron temperatures.

The average \( B_\perp \) rotates smoothly from positive to negative. The large standard deviation of \( B_\perp \) within the exhaust region is evidence of the large variability in \( B_\perp \) profiles between events. Traces for individual events show more clearly that some events undergo large changes in \( B_\perp \) very close to the exhaust boundary (i.e., near \( y = [0,1] \)). These events are likely to have bifurcated current sheets [Mistry et al., 2015]. It is worth noting that the range of \( y \) over which the change in \( B_\perp \) occurs is affected by the time normalization. If large changes in \( B_\perp \) occur over a fixed spatial scale, they will appear to be very thin in Figure 6 if the exhaust is particularly thick. The mean \( B_\perp \) is therefore affected by the measured \( B_\perp \) profile as well as the exhaust width. With such a large set of events, however, the mean trace is still expected to be representative of the average \( B_\perp \) profile far downstream of the X line.

The out-of-plane magnetic field, on average, increases in the exhaust region and remains enhanced throughout the exhaust. The amount by which \( B_{\text{avg}} \) increases varies considerably, as illustrated by the large standard deviation in Figure 6b in the center of the exhausts. \(|B|\) decreases within the exhausts (the extent of which is a function of the reconnection guide field). On average \( B_{\text{avg}} \) is zero. This is expected given that the hybrid-MVA method of defining \( LMN \) coordinates forces \( B_{\text{avg}} \) to be zero at the exhaust boundaries.

The exhaust outflow speed is shown in Figure 6d. The superposed epoch analysis shows \( V_\parallel \) to reach a maximum of 0.79 ± 0.34 \( C_{\text{AS}} \) (where the quoted uncertainty is the standard deviation of all events), indicating that on average the exhaust outflow speed is less than the inflow region Alfven speed. This has been noted in several previous studies [e.g., Enßl et al., 2014; Gosling et al., 2006a]. On average the ion velocity in the out-of-plane direction \( V_\perp \) and in the current sheet normal direction \( V_\parallel \) are zero (Figures 6e and 6f). \( V_\perp \) does not show any signature of plasma inflow into the exhaust, which is typically very difficult to measure in the solar wind [Mistry et al., 2015].

The ion density and temperature both increase within the exhausts (Figures 6h–6i). The superposed epoch analysis shows a maximum increase in ion density of 19 ± 26% and ion temperature of 28 ± 57% (where the quoted uncertainty again is the standard deviation of all events). We attribute this large degree of variability to differences in the reconnection guide field strength and inflow region plasma beta, as shall be shown in the following section.

The thermal pressure increases within the exhausts, and the magnetic pressure decreases (Figures 6j and 6k), such that the total pressure remains constant throughout the exhaust (Figure 6l). As noted above, the electron thermal pressure within each reconnection exhaust was assumed to vary linearly between the two inflow regions. Assuming that the electron temperature does not increase within the exhaust is reasonable considering that ion heating within magnetopause reconnection exhausts has been measured to be ~8 times larger than electron heating [Phan et al., 2014] and that increases in electron temperature within magnetopause reconnection exhausts is approximately 0.017 \( m_{\text{eAS}} C_{\text{AS}} \) [Phan et al., 2013]. For the median inflow region Alfven speed of the events in this survey (35.6 km s\(^{-1}\)) this corresponds to an increase in temperature of 0.22 eV, which is negligible with respect to the median electron temperature in the inflow regions (12.4 eV). Electron heating was observed for one of the events in this data set with an unusually high Alfven speed [Pulupa et al., 2014]; however, in general, electron heating is not observable in solar wind reconnection exhausts [Gosling, 2012; Pulupa et al., 2014].

We note that values shown within the exhaust region are affected by the uncertainty of the mean inflow region values with which they are normalized. The uncertainties of these mean values are small, however.
Across the 188 events, the maximum uncertainty in the mean measurement of any field component is 0.03, the maximum for any ion velocity component is 0.13, the maximum for the ion density is 0.03, and the maximum for the ion temperature is 0.08 (in normalized units), although these values were significantly smaller for the majority of events. Uncertainties in the mean inflow region velocities may therefore contribute to the uncertainty in the exhaust region velocities; however, this effect is not significant for the magnetic field, ion density, and ion temperature. Estimates of the uncertainty in the mean inflow region electron temperature are not possible as only one or two data points are available for each inflow region.

4. Effects of Plasma Beta and Guide Field

Figure 6 shows that on average the plasma density, ion temperature, thermal pressure, and out-of-plane magnetic field increase within reconnection exhausts and that the magnetic pressure decreases. There is, however, a large degree of variability between events. This is not surprising given that while many previously studied events exhibit an increase in the ion density and temperature within the exhaust region [e.g., Gosling et al., 2005], other events have also been observed with a clear absence of these signatures [Gosling, 2007; Gosling et al., 2007a]. Furthermore, we note that the events within this data set occur over a wide range of guide fields (0–10) and inflow region plasma beta (0.1–6.6).

Figure 7 shows superposed epoch analyses for the 188 events grouped into four guide field bins, with 1/4 of the events (47) in each bin. When the guide field is weak the decrease in $|B|$ (and corresponding magnetic pressure) and the increases in ion density ($n_i$), ion temperature ($T_i$), and thermal pressure are substantial. At larger guide fields, the profiles of these parameters vary in a similar manner; however, the changes are reduced in amplitude. If the lowest guide field bin is excluded, the amplitude of the increase in $B_{\text{in}}$ also appears to decrease at larger guide fields. This is not inconsistent with simulations by Rogers et al. [2003], who looked at $B_{\text{in}}$ much closer to the X line. The relationship between the enhancement in $B_{\text{in}}$ and the guide field for low values of $B_{\text{in}}$ is not clear in our data set, however.

The dependence of $n_i$ and $T_i$ on the guide field can be understood by considering that these events are in pressure balance, which is shown in Figure 6b. It is also shown in Figure 8 where the magnetic pressure, thermal pressure, and total pressure in the inflow regions and at the midpoint of the exhausts (at $y = 0.5$) are compared without normalization. The contribution of the magnetic pressure and thermal pressure to the total pressure is characterized by the plasma beta. For a plasma beta much greater than 1, for example, the thermal pressure contributes to almost all of the total pressure, and the magnetic pressure is negligible. Consequently, at the current sheet center where the magnetic pressure decreases, only a small increase in thermal pressure is required to maintain pressure balance. The increases in density and ion temperature are therefore expected to be small.

In the zero guide field limit, the condition for pressure balance using the thermal pressures ($P_{\text{th,in}}$) and magnetic pressures ($P_{\text{th}}$) in the inflow region (subscript "in") and central exhaust region (subscript "exh") may be expressed as

$$P_{\text{th,in}} + P_{\text{th,exh}} = P_{\text{th,exh}}.$$  \hspace{1cm} (1)

since in the central exhaust region the magnetic pressure is negligible. This can be rearranged to

$$1 + \frac{1}{\beta_{\text{in}}^{\text{th,in}}} = \frac{P_{\text{th,exh}}}{P_{\text{th,in}}}.$$ \hspace{1cm} (2)

where $\beta_{\text{in}}$ is the inflow region plasma beta. In the case of zero guide field the relative increase in thermal pressure in the exhaust region ($P_{\text{th,exh}}/P_{\text{th,in}}$) is therefore dictated by the inflow region plasma beta.

For nonzero guide fields the relationship between the increase in the out-of-plane field and the guide field is not known. The magnetic pressure within the exhaust region is therefore not known, and it is not possible to analytically determine a simple $P_{\text{th,exh}}/P_{\text{th,in}}$ scaling as it was for the zero guide field limit (where the exhaust region magnetic pressure is zero). Figure 9a shows, however, that the observed relative increase in thermal pressure is controlled by both the inflow region beta and guide field. Events with the smallest guide fields
are closest to the line given by equation (2), as expected. Events with the same plasma beta but larger guide fields have smaller increases in the thermal pressure.

Based on the analysis shown in Figure 9a, an equation of the following form was fitted to the data to derive an empirical relation between the guide field and inflow region plasma beta using 188 solar wind exhausts,

\[ \frac{P_{\text{th,exh}}}{P_{\text{th,in}}} = \beta_{\text{in}}^a + B_G^b + c \]  

as well as an equation of the form

\[ \frac{P_{\text{th,exh}}}{P_{\text{th,in}}} = \beta_{\text{in}}^a B_G^b + c \]  

These functional forms are motivated by \( \frac{P_{\text{th,exh}}}{P_{\text{th,in}}} \) following equation (2) in the case of nonzero guide field. A best fit to the data using equation (3) yielded an \( R^2 \) value of 0.63, whereas a best fit to the data using equation (4) yielded an \( R^2 \) value of 0.75 with coefficients \( a = -0.44 \), \( b = -0.29 \), and \( c = 0.36 \).
The measured values of $P_{\text{th,exh}}/P_{\text{th,in}}$ are compared to values predicted using equation (4) in Figure 10a. A contour plot of the empirical relationship between $P_{\text{th,exh}}/P_{\text{th,in}}$, $\beta_{\text{in}}$, and $B_G$ as given by equation (4) is also shown in Figure 10b. This relationship predicts the increase in thermal pressure from inflow region to the exhaust region, given the guide field and the inflow region plasma beta. We note, however, that equation (4) does not tend to 1 at large values of $\beta_{\text{in}}$ or $B_G$ as would be expected; therefore, this empirical fit does not seem valid where it gives $P_{\text{th,exh}}/P_{\text{th,in}} < 1$.

A physical interpretation of this fit can be understood by considering the pressures in the exhaust. Within the exhaust $B_L$ decreases and $B_M$ increases, however, the net effect is that both $B_L$ and the total magnetic pressure decrease. Consequently, the thermal pressure must increase (facilitated by increases in the density and/or ion temperature). The magnetic pressure is low for large $\beta_{\text{in}}$; therefore, the necessary increase in thermal pressure (i.e., $P_{\text{th,exh}}/P_{\text{th,in}}$) is small. If there is a large guide field a small proportion of the total field will reconnect and the decrease in magnetic pressure will be small, further reducing the necessary increase in $P_{\text{th,exh}}/P_{\text{th,in}}$. The relative thermal pressure increase is therefore a function of both the inflow region plasma beta and the guide field.

The relative increases in the constituents of the thermal pressure (density and temperature) show similar trends (Figures 9b and 9c). Increases in temperature tend to be larger than density (as shown in Figures 6 and 7), which is why there is a gap between the data and the line in Figure 9b, and why some data are to the right of the line in Figure 9c. There are also some events where the exhaust region density or ion temperature is reduced with respect to the inflow region; however, the product of the density and temperature is such that the normalized exhaust region thermal pressure is always greater than 1.

### 5. Ion Bulk Heating

In this section we focus on the increase in ion temperature within the exhaust region, which has previously been measured to be 13% of the available magnetic energy to each proton-electron pair in the solar wind [Drake et al., 2009] and magnetopause [Phan et al., 2014]. The temperature increase is measured as the difference between the ion temperature in the inflow region and the exhaust region. Since there is a notable difference in ion temperature between the two inflow regions for a small number of events, we define the inflow region temperature to be the effective inflow region temperature

$$T_{\text{in}} = \frac{n_1 T_{\text{in,1}}/|B_{L1}| + n_2 T_{\text{in,2}}/|B_{L2}|}{n_1 |B_{L1}| + n_2 |B_{L2}|},$$

where the subscripts “1” and “2” refer to average values from each inflow region [Phan et al., 2014].

The maximum difference between this inflow temperature and the inflow temperature defined as the average of $T_i$ in inflow regions 1 and 2 is 26%; however, it is less than 4% for three quarters of the events. To measure the amount by which ions are heated within the exhaust region, the 90% quantile of the ion temperature is used. The increase in ion temperature ($\Delta T_i$) is defined as the 90% quantile exhaust region temperature minus $T_{\text{in,eff}}$. The 90% quantile is used rather than the maximum measured ion temperature to avoid outlying data points unduly affecting the calculation. We note, however, that the difference between the 90% quantile and the maximum exhaust temperature is less than 10% for 90% of the events.
Figure 11 shows the increase in ion temperature as a function of \( m_i C_{AS}^2 \) for the 188 events. Measurement uncertainties for \( \Delta T_i \) and \( m_i C_{AS}^2 \) are calculated using the standard deviation of measurements in inflow regions 1 and 2. Best fit to these data show that \( \Delta T_i = 0.12 m_i C_{AS}^2 \pm 0.01 m_i C_{AS}^2 \) (95% confidence interval), with regression coefficient \( R^2 = 0.81 \). This is consistent with previous measurements of 22 events in the solar wind [Drake et al., 2009] and 87 events at the magnetopause [Phan et al., 2014]. Černý et al. [2014] report larger heating rates of \( \Delta T_i = 0.2 m_i V_{ex}^2 \) from a survey of 418 solar wind events, where \( V_{ex} \) is the measured exhaust outflow speed (which is comparable to \( C_{AS} )\). The cause of the discrepancy between these results is not clear; however, the correlation between the exhaust outflow speed and the increase in ion temperature is significantly weaker in the Černý et al. [2014] study as compared to the present study and the results of Drake et al. [2009] and Phan et al. [2014].

These results extend upon previously published analysis, and we have tested this relationship with guide fields of up to \( B_G = 10 \). The largest guide fields in the studies of Drake et al. [2009], Phan et al. [2014], and Černý et al. [2014] were 0.6, 2.7, and 3.7, respectively. We find that large guide field events show a very weak correlation between \( \Delta T_i \) and \( m_i C_{AS}^2 \); the regression coefficients for events with guide fields of \( B_G < 0.59 \), \( 0.59 < B_G < 1.15 \), \( 1.15 < B_G < 2.17 \), and \( B_G > 2.17 \) are \( R^2 = 0.86 \), 0.86, 0.54, and 0.08, respectively. At large guide fields the reconnecting component of the field (\( B_L \)) tends to be small, reducing \( C_{AS}^2 \). The measured
values of $\Delta T_i$ and $m_i C_{AS}^2$ are therefore small and comparable to the measurement error, making it difficult to reliably determine any correlation between the increase in ion temperature and the available magnetic energy.

6. Discussion

While the density and temperature have been observed to increase within reconnection exhausts, the superposed epoch analysis also shows that the out-of-plane field increases (Figure 6b). Of key importance is that the increase in density, temperature, and $B_M$ occurs in conjunction with each other and that they remain enhanced throughout the exhaust region. These increases in $B_M$ are not an artefact of the superposed epoch analysis and can be seen in a large proportion of individual events.

The fact that $B_M$ is enhanced throughout the exhaust region has implications for the structure of the exhaust boundaries. The plasma density and temperature increase at MHD slow shocks which form along the exhaust boundaries in the Petschek [1964] reconnection model. These shocks also reduce $B_L$ from its inflow region value to zero, and $B_M$ is zero everywhere. While this model is often cited in relation to observed density and temperature enhancements at reconnection exhausts, strictly, it is only applicable to reconnection of purely antiparallel magnetic fields.

While slow shocks do form in one-dimensional simulations of antiparallel reconnection, rotational discontinuities propagate ahead of the slow shocks as soon as the upstream fields are changed to a non-antiparallel configuration [Y Lin and Lee, 1993]. These MHD rotational discontinuities rotate the field out of the reconnection plane, reducing $B_L$ and increasing $B_M$. $B_M$ does not remain enhanced throughout the exhaust region, however, as slow shocks

Figure 10. (a) Observed values of the normalized increase in thermal pressure, compared against the expected increase according to an empirical fit to the data (equation (4)). (b) Contour plot of normalized increase in thermal pressure as a function of inflow region plasma beta and guide field, determined from an empirical fit to the data (equation (4) with coefficients $a = -0.44$, $b = -0.29$, and $c = 0.36$).

Figure 11. Increase in ion temperature as a function of $m_i C_{AS}^2$. The line and shaded region show the best fit to the data and 95% confidence interval ($\Delta T_i = 0.12 \pm 0.01 m_i C_{AS}^2$).
downstream of the rotational discontinuities decrease $B_M$. This is inconsistent with the observations presented here. The shocks also increase the density and temperature, such that increases in $B_M$, density, and temperature are not co-located.

The out-of-plane field does remain enhanced in hybrid simulations with guide fields of $B_G \sim 0.5$, however [Y Lin and Lee, 1995; Y Lin and Swift, 1996]. In this case, the ability of the ions to acquire a temperature anisotropy modifies the Rankine-Hugoniot jump relations, allowing plasma density and temperature changes to occur at the rotational discontinuity itself [Hudson, 1971]. At significant enough guide fields, changes in the field, density, and temperature at the slow shocks become very weak due to temperature anisotropy modifications [Y Lin and Lee, 1993]. The consequence of this is that the decrease in $B_L$ and increases in $B_M$, density, temperature, and exhaust velocity are co-located and achieved via the anisotropic rotational discontinuities entirely rather than slow shocks, and that $B_M$ remains enhanced throughout the exhaust region.

The results of this superposed epoch analysis closely resemble these 1-D hybrid simulations [Y Lin and Lee, 1995; Y Lin and Swift, 1996], where rotational discontinuities are responsible for the increase in $B_M$ within the exhaust region and the slow shocks become significantly weakened for $B_G > 0.5$ (events in this analysis have a median guide field of $B_G \approx 1.2$). We do not, however, have sufficiently high-resolution measurements for these events to test whether they fulfill the anisotropic jump conditions for rotational discontinuities and slow shocks. This would require the cadence of plasma measurements (including temperature anisotropies) to be comparable to the timescales over which the field varies (i.e., less than 1 s), so that the jump conditions can be tested using measurements immediately upstream and downstream of the exhaust boundaries. This may be possible with future solar wind missions such as THOR [Vaivads et al., 2016].

The superposed epoch analysis therefore suggests that solar wind exhausts may generally be well described using fluid theories that permit a temperature anisotropy. In 8 out of these 188 events, however, the overall increase in $B_M$ was also accompanied by a decrease in $B_M$ along a narrow region close to the exhaust boundaries, consistent with the presence of Hall magnetic fields [Mistry et al., 2016]. This region cannot be detected in the superposed epoch analyses as the vast majority of events do not show clear evidence of Hall fields and the region of reduced $B_M$ is only a small fraction of the overall exhaust width. The conditions under which Hall magnetic fields remain observable far downstream of the reconnection X line remain unclear. Nevertheless, the increase in the out-of-plane field occurs in both exhausts with and without clear evidence of Hall magnetic field reductions.

Some reconnection exhausts in the solar wind have been observed with clear enhancements in the exhaust region density and ion temperature, but in other events these enhancements are absent. Our analysis indicates that increases in the thermal pressure are expected to be weak for large reconnection guide fields and inflow region plasma beta; therefore, in both cases the ion density and ion temperature in the exhaust region should be comparable to the inflow region. In fact, many previously studied events which did not have ion density or temperature enhancements had either large guide fields [Gosling et al., 2007a] or were observed in the high-speed solar wind [Gosling, 2007], which tends to have a larger plasma beta than the slow solar wind.

This dependence is qualitatively consistent with the measured scaling of the ion heating with inflow region Alfvén speed. The total field magnitude in the solar wind does not vary significantly, and is typically ~5 nT. For large guide fields the reconnecting component of the field ($B_L$) is small, as is $C_{AS}$; hence, $\Delta T_i$ is expected to be small. Additionally, for large plasma beta the Alfvén speeds tend to be small; therefore, $\Delta T_i$ is again expected to be small. At large guide fields $C_{AS}$ is too small to measure the scaling between $C_{AS}$ and $\Delta T_i$ in the solar wind. Measurements in plasmas with higher Alfvén speeds where the guide fields are also large are required to test whether this scaling also holds under significant guide fields.

In this study we have used a superposed epoch analysis to extract the average properties of 188 solar wind reconnection exhausts. The out-of-plane field is clearly enhanced in the exhaust region, which is consistent with one-dimensional simulations [Y Lin and Lee, 1995; Y Lin and Swift, 1996]. This suggests that, in general, exhausts far downstream of the X line are well modeled without the need for a detailed treatment of kinetic processes (although the presence of Hall fields in some events suggests that this is not always the case [Mistry et al., 2016]). The large variability in observations between different solar wind exhausts makes it difficult to
determine their average properties. This analysis has revealed, however, that the inflow region plasma beta and reconnection guide field is partly responsible for this variability, both of which have broader ranges in the solar wind than in many other reconnection environments.

Acknowledgments

Wind data are available from CDAWeb (cdaweb.gsfc.nasa.gov). This work was supported by the Turboplasmas project and UK STFC through the award of a studentship (R.M.) and grant ST/G00725X/1 (J.P.E.).

References

Borovsky, J. E. (2008), Flux tube texture of the solar wind: Strands of the magnetic carpet at 1 AU, J. Geophys. Res., 113, A08110, doi:10.1029/ 2007JA012684.
Cassak, P. A., and M. A. Shay (2007), Scaling of asymmetric magnetic reconnection: General theory and collisional simulations, Phys. Plasmas, 14(10) 102114.
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.
Doss, C. E., C. Komar, P. A. Cassak, F. D. Wilder, S. Eriksson, and J. F. Drake (2015), Asymmetric magnetic reconnection with a flow shear and applications to the magnetopause, J. Geophys. Res. Space Phys., 120, 7748–7763, doi:10.1002/2015JA021489.
Drake, J. F., M. Swisdak, T. D. Phan, P. A. Cassak, M. A. Shay, S. T. Lepri, R. P. Lin, E. Quataert, and T. H. Zurbuchen (2009), Ion heating resulting from pickup in magnetic reconnection exhausts, J. Geophys. Res., 114, A05111, doi:10.1029/2008JA013701.
Enßl, J. L., P. Plich, J. Sfránková, and Z. Nemeček (2014), Statistical study of reconnection exhausts in the solar wind, Astrophys. J., 796(1), 21.
Gosling, J. T. (2007), Observations of magnetic reconnection in the turbulent high-speed solar wind, Astrophys. J. Lett., 671(1), L73.
Gosling, J. T., S. Eriksson, and R. Schwenn (2006a), Petschek-type magnetic reconnection exhausts in the solar wind well inside 1 AU: Helios, J. Geophys. Res., 111, A06102, doi:10.1029/2005JA011863.
Gosling, J. T., S. Eriksson, R. M. Skoug, D. J. McComas, and R. J. Forsyth (2006b), Petschek-type reconnection exhausts in the solar wind well beyond 1 AU: Ulysses, Astrophys. J., 644(1), 613.
Gosling, J. T., S. Eriksson, D. J. McComas, T. D. Phan, and R. M. Skoug (2007a), Multiple magnetic reconnection sites associated with a coronal mass ejection in the solar wind, J. Geophys. Res., 112, A08106, doi:10.1029/2006JA011848.
Gosling, J. T., T. D. Phan, R. P. Lin, and A. Szabo (2007b), Prevalence of magnetic reconnection at small field shear angles in the solar wind, Geophys. Res. Lett., 34, L15110, doi:10.1029/2007GL030706.
Horbury, T. S., D. Burgess, M. Fränz, and C. J. Owen (2001), Three spacecraft observations of solar wind discontinuities, Geophys. Res. Lett., 28(4), 677–680, doi:10.1029/2000GL001211.
Hoshino, M., T. Mukai, T. Yamamoto, and S. Kokubun (1998), Ion dynamics in magnetic reconnection: Comparison between numerical simulation and Geotail observations, J. Geophys. Res., 103(A3), 4599–4530, doi:10.1029/97JA01785.
Hudson, P. D. (1971), Rotational discontinuities in an anisotropic plasma, Planet. Space Sci., 19(12), 1693–1699.
Innocenti, M. E., M. Goldman, D. Newman, S. Markidis, and G. Lapenta (2015), Evidence of magnetic field switch-off in collisionless magnetic reconnection, Astrophys. J., 810(2), L19.
Knetter, T. F. M. Neubauer, T. Horbury, and A. Balogh (2004), Four-point discontinuity observations using Cluster magnetic field data: A statistical survey, J. Geophys. Res., 109, A06102, doi:10.1029/2003JA010099.
Lepping, R. P., et al. (1995), The Wind magnetic field investigation, Space Sci. Rev., 71(1–4), 207–229.
Lin, R. P., et al. (1995), A three-dimensional plasma and energetic particle investigation for the wind spacecraft, Space Sci. Rev., 71(1–4), 125–153.
Lin, Y., and L. C. Lee (1993), Structure of reconnection layers in the magnetosphere, Space Sci. Rev., 65(1–2), 59–179.
Lin, Y., and L. C. Lee (1995), Simulation study of the Riemann problem associated with the magnetotail reconnection, J. Geophys. Res., 100(A10), 19,227–19,237, doi:10.1029/94JA01549.
Lin, Y., and D. W. Swift (1996), A two-dimensional hybrid simulation of the magnetotail reconnection layer, J. Geophys. Res., 101(A9), 19,859–19,870, doi:10.1029/95JA01457.
Liu, Y. H., J. F. Drake, and M. Swisdak (2012), The structure of the magnetic reconnection exhaust boundary, Phys. Plasmas, 19, 022110.
Mistry, R. J. P. Eastwood, T. D. Phan, and H. Hietala (2015), Development of bifurcated current sheets in solar wind reconnection exhausts, Geophys. Res. Lett., 42, 10,513–10,520, doi:10.1002/2015GL066820.
Mistry, R. J. P. Eastwood, C. C. Hagverty, M. A. Shay, T. D. Phan, H. Hietala, and P. A. Cassak (2016), Observations of Hall reconnection physics far downstream of the X-line, Phys. Rev. Lett., 117(18), 185102.
Petschek, H. (1964), Magnetic field annihilation, NASA Spec. Publ., (50), 425–439.
Pfellows, D. T., et al. (2004), A magnetic reconnection X-line extending more than 390 Earth radii in the solar wind, Nature, 439(7073), 175–178.
Phan, T. D., G. Paschmann, C. Twitty, F. S. Mozer, J. T. Gosling, J. P. Eastwood, M. Øieroset, H. Rème, and E. A. Lucek (2007), Evidence for magnetic reconnection initiated in the magnetosheath, Geophys. Res. Lett., 34, L14104, doi:10.1029/2007GL030343.
Phan, T. D., J. T. Gosling, and M. S. Davis (2009), Prevalence of extended reconnection X-lines in the solar wind at 1 AU, Geophys. Res. Lett., 36, L09108, doi:10.1029/2009GL037773.
Phan, T. D., J. T. Gosling, G. Paschmann, C. Psma, J. F. Drake, M. Øieroset, D. Larson, R. P. Lin, and M. S. Davis (2010), The dependence of magnetic reconnection on plasma β and magnetic shear: Evidence from solar wind observations, Astrophys. J. Lett., 719(2), L199.
Phan, T. D., M. A. Shay, J. T. Gosling, M. Fujimoto, J. F. Drake, G. Paschmann, M. Øieroset, J. P. Eastwood, and V. Angelopoulos (2013), Electron bulk heating in magnetic reconnection at Earth’s magnetopause: Dependence on the inflow Alfvén speed and magnetic shear, Geophys. Res. Lett., 40, 4475–4480, doi:10.1002/2012GL050917.
Phan, T. D., J. F. Drake, M. A. Shay, J. T. Gosling, G. Paschmann, J. P. Eastwood, M. Øieroset, M. Fujimoto, and V. Angelopoulos (2014), Ion bulk heating in magnetic reconnection exhausts at Earth’s magnetopause: Dependence on the inflow Alfvén speed and magnetic shear angle, Geophys. Res. Lett., 41, 7002–7010, doi:10.1002/2014GL061547.
Pulupa, M. P., C. Salem, T. D. Phan, J. T. Gosling, and S. D. Bale (2014), Core electron heating in solar wind reconnection exhausts, Astrophys. J. Lett., 791(1), L17.
Rogers, B. N., R. E. Denton, and J. F. Drake (2003), Signatures of collisionless magnetic reconnection, J. Geophys. Res., 108(A3), 1111, doi:10.1029/2002JA009699.

Runov, A., V. Angelopoulos, X. Z. Zhou, X. J. Zhang, S. Li, F. Plaschke, and J. Bonnell (2011), A THEMIS multicase study of dipolarization fronts in the magnetotail plasma sheet, J. Geophys. Res., 116, A05216, doi:10.1029/2010JA016316.

Sonnerup, B., and L. J. Cahill (1967), Magnetopause structure and attitude from Explorer 12 observations, J. Geophys. Res., 72(1), 171–183, doi:10.1029/JZ072i001p00171.

Swisdak, M., M. Opher, J. Drake, and F. A. Bibi (2010), The vector direction of the interstellar magnetic field outside the heliosphere, Astrophys. J., 710(2), 1769.

Vaivads, A., et al. (2016), Turbulence Heating ObserveR—Satellite mission proposal, J. Plasma Phys., 82(5).

Vasyliunas, V. M. (1975), Theoretical models of magnetic field line merging, Rev. Geophys., 13(1), 303–336, doi:10.1029/RG013i001p00303.