RECONNECTION OUTFLOW GENERATED TURBULENCE IN THE SOLAR WIND

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ABSTRACT

Petschek-type time-dependent reconnection (TDR) and quasi-stationary reconnection (QSR) models are considered to understand reconnection outflow structures and the generation of local turbulence in the solar wind. Comparing TDR/QSR model predictions of the outflow structures with actual measurements shows that both models can explain the data equally well. It is demonstrated that the outflows can often generate more or less spatially extended turbulent boundary layers. The structure of a unique extended reconnection outflow is investigated in detail. The analysis of spectral scalings and spectral break locations shows that reconnection can change the local field and plasma conditions which may support different local turbulent dissipation mechanisms at their characteristic wavenumbers.

Key words: magnetic reconnection – solar wind – turbulence

Online-only material: color figures

1. INTRODUCTION

The reduced power spectral density (PSD) of turbulent magnetic fluctuations in the solar wind is known to follow power-law scaling $f^{-\alpha}$ with spectral index close to $\alpha = 5/3$ (Kolmogorov scaling) or $\alpha = 3/2$ (Iroshnikov–Kraichnan scaling) over the inertial range of scales (see, e.g., Bruno & Carbone 2013). Recently, much attention has been devoted to the turbulent heating of solar wind plasma, which occurs over characteristic ion/proton (Smith et al. 2006; Bourouaine et al. 2012) or/and electron scales (Alexandrova et al. 2009; Chen et al. 2013), where the PSDs exhibit spectral breaks.

Large-scale velocity shears, for example, regions of interacting fast and slow solar wind, can drive a turbulent cascade (Roberts et al. 1992) and turbulence can heat the plasma. In this Letter, we are interested in reconnection outflows in the solar wind that generate velocity shears and interact with the background plasma in a complex way. To study reconnection-outflow-associated structures, we use WIND magnetic (fluxgate magnetometer, time resolution 3 s and 0.092 s; Lepping et al. 1995) and plasma data (time resolution 3 s and 92 s; Lin et al. 1995; Ogilvie et al. 1995). We study the database of reconnection outflow events compiled by Phan et al. (2009). A unique long-duration event from this database is considered in detail in Section 2. To explain the data, we consider reconnection scenarios that predict different reconnection outflow structures. The limitations of one-point WIND measurements affecting the interpretation of data in terms of reconnection models is demonstrated. In Sections 3 and 4, using the Morlet wavelets, we adaptively estimate the reduced PSDs for our selected events. Discussions and conclusions are presented in the last section.

2. RECONNECTION OUTFLOW STRUCTURE

We consider two Petschek-type reconnection scenarios: time-dependent reconnection (TDR; Heyn & Semenov 1996; Semenov et al. 2004; Sasunov et al. 2012) and quasi-stationary reconnection (QSR; Gosling et al. 2005; Phan et al. 2009; Gosling 2012). According to the TDR model (Figure 1, left) an unstable current sheet (tangential discontinuity; TD), via reconnection, decays into a system of moving large-amplitude fast, slow, Alfvén, and entropy waves. The waves propagate symmetrically outward from the reconnection site along the current sheet together with the reconnect plasma and magnetic flux, collectively forming the reconnection outflow region with embedded discontinuities and a propagating flux tube of finite width. Observations of the structures in Figure 1 (left) depend on the geometry of crossings. Along the indicated trajectory (dashed magenta arrow), the border of a flux tube can be Kelvin–Helmholtz (KH) unstable TD (Sasunov et al. 2012) generating turbulence behind the moving structure.

According to the QSR model (Figure 1, right), reconnection proceeds for a long time in a quasi-steady way, producing a space-filling, wedge-shaped reconnection exhaust. Here the newly reconnected field lines associated with the plasma inflow through the separatrix layer are strongly kinked. The kinks representing a pair of Alfvénic disturbances or rotational discontinuities (RDs) in the inflow regions are accelerating plasmas to the exhaust from both sides as they propagate along the magnetic field away from the reconnection site. Since many exhausts contain plasmas with decreased magnetic field and enhanced proton density and temperature, the transition to the exhaust is often a slow-mode shock. It was found by Huttunen et al. (2007) that wave activity at the ion–acoustic range and near the electron plasma frequency is preferentially observed near the reconnection X lines or along the exhaust boundaries. These are the regions of large density and temperature gradients, anisotropies, and shear flows. These are the expected QSR model structures along a trajectory (dashed magenta arrow).

Figure 2 shows a reconnection outflow event that occurred on 1998 September 1. Figures 2(a) and (b) show the bulk speed components and the local Alfvén speed. The borders of the reconnection outflow seen mainly in $V_Z$ are indicated by vertical blue lines. Figures 2(c) and (d) show the magnetic field magnitude, components, longitudinal, and latitudinal directional changes of $\mathbf{B}$. The $B_Z$ magnetic component is changing sign across the reconnection current layer. Within the outflow, the
magnetic field direction does not change significantly. Since \( B_Y \sim 0 \) (nT), the direction of the flux tube axis (TDR model) or the magnetic field direction within the space filling outflow (QSR model) is determined by \( \langle B_X \rangle \sim -2.5 \) (nT) and \( \langle B_Z \rangle \sim 2.5 \) (nT). Figures 2(e) and (f) show the proton density and temperature, respectively.

By using MHD stability criteria and analytical calculations, it has already been suggested that for this event the outflow (a flux tube in TDR model) is bordered by TDs. The first TD at 1.31 UT was found to be KH stable. However, when the RDs and slow shocks merge, as may be the case near 1.31 UT, the signatures of TD are observed (Sasunov et al. 2012) and the TDR (flux tube crossing) and QSR (exhaust boundary crossings) models cannot be distinguished. In fact, at 1.31 UT (left border of the outflow), \( B \) decreases, both \( N_p \) and \( T_p \) increase, \( \phi(B) \) and \( \theta(B) \) show no significant directional changes. The second TD at 1.59 UT (right border of the outflow) was suggested to be KH unstable by Sasunov et al. (2012). Yet, due to the strong local fluctuations, it is impossible to distinguish between RD and TD without invoking the analytical model in Sasunov et al. (2012).

For this reason, we do not assign any kinds of discontinuities to the outflow borders. Instead, we treat the entire interval from 1.54 UT (starting within the outflow; red vertical line) until 1.8 UT as a turbulent boundary layer (TBL). We suppose that the fluctuations within this boundary layer are driven by the predominantly vertical \( (V_Z \sim -50 \text{ km s}^{-1}) \) outflow rather than by the normally occurring outflow-independent processes in the solar wind. This supposition is based on the following arguments. (1) The fluctuations (e.g., seen in \( V_X \), \( B_X \)) exhibit the largest amplitudes closer to the outflow border becoming weaker further away from their source. (2) The highest proton temperatures are observed at the outflow boundary, then \( T_p \) slowly decreases until 1.8 UT, reaching the background level of solar wind proton temperatures before 1.3 UT (red vertical dashed lines in Figure 2(f)). Temperature fluctuations are correlated with density fluctuations. This indicates that the plasma is mixing and cooling within the boundary layer. (3) There exist (anti)correlated fluctuations between speed, magnetic field, density, and temperature fluctuations associated with strong azimuthal directional changes of the magnetic field \( \phi(B) \) (Figure 2(d)). In the database of reconnection outflows (Phan et al. 2009), similar changes in \( \phi(B) \) occur frequently, often associated with crossings of the outflow borders. In this event, the changes of \( \phi(B) \) reflect the changes of the sign of \( B_X \) (Figure 2(c)). (4) The scaling properties of magnetic fluctuations are the same within the entire TBL (see below; Figures 3(e) and (f)).

Again, we are not able to differentiate between boundary layer fluctuations that can occur in TDR and QSR models. When
the flux tube develops as it is suggested in the TDR model, KH unstable boundary (TD), and KH turbulence can develop. This is supported by the fact that the shear in $V_2$ across the outflow boundary or TD is larger than the local Alfvén speed (Figure 2(b)). The strong directional changes $\phi(B)$ correlated with field and plasma fluctuations can indicate KH-instability-associated vorticity and vortex shedding (Sasunov et al. 2012) or reconnection-outflow layers (Liu et al. 2012), and nonstationarity effects (Vörös et al., 2014 December 10). Although for strongly fluctuating $\phi(B)$ the occurrence of linear waves can be excluded, turbulence in the separatrix layer of the QSR model still can account for the observed changes as this is the region where the strongest fluctuation activity and instabilities can be expected (Huttunen et al. 2007). Changes in $\phi(B)$ can also correspond to crossings of turbulence-generated structures (Greco et al. 2009) or reconnection-associated current sheet flappings (Vörös et al. 2009). In any case, we suggest that the fluctuations are driven by the reconnection outflow in both models. The next section is devoted to the analysis of the scaling features of fluctuations across the event in Figure 2.

3. NONSTATIONARITIES AND STRUCTURES WITHIN RECONNECTION OUTFLOW LAYERS

Contrary to the commonly used lengths of data in the studies of solar wind turbulence (Smith et al. 2006; Bourouaine et al. 2012; Alexandrova et al. 2009; Chen et al. 2013), our intervals are rather short (see Figure 1) and extreme care is needed to identify the physical processes that can influence the scaling features. To avoid spurious scaling estimations along the event crossing, we estimate parameters that can distort the reduced PSD. We consider the angle between the magnetic field and velocity vectors, $\eta(B, V)$, the pressure anisotropy parameter $\epsilon = 1 - \mu_0(P_1 - P_2)/B^2$ ($\mu_0$—magnetic permeability, $P_1, P_2$—pressures parallel and perpendicular to the magnetic field; Liu et al. 2012), and nonstationarity effects (Vörös et al. 2004, 2007). Although the angle $\eta$ is computed from instantaneous values of $B$ and $V$, it corresponds to $\eta(B, V)$ ($B$ is the mean field) when the magnetic field direction is not changing locally. In such cases $\eta(B, V)$ controls the population of aligned or perpendicular fluctuations relative to the local magnetic field. The expected scaling indices are $\alpha_{||} = 2$ and $\alpha_{\perp} = 5/3$, respectively. It is roughly found that for $\eta(B, V) < 30^\circ$ the contribution of field-aligned fluctuations begins to be significant (Horbury et al. 2008). Counterstreaming protons within reconnection outflows increase the proton pressure/temperature along the magnetic field (Liu et al. 2012), leading to $\epsilon \neq 1$, which can distort the spectrum near proton scales (Bale et al. 2009).

Nonstationarity effects are recognized by estimating PSDs within two overlapping and non-overlapping sliding windows of different lengths (0.1 and 0.05 h). Figure 3 shows the reconnection outflow in $V_2$, the parameters $\epsilon, \eta$, and the estimated spectral features, explained below. The outflow borders and the TBL are indicated by vertical blue and red lines, respectively. The PSDs are computed from the high-resolution total magnetic field $B$. The scaling indices ($\alpha_{||}$ and $\alpha_{\perp}$), obtained from PSD fits over the high- (subscripts hf) and low-frequency (subscripts Lf) ranges, calculated within the two sliding windows (subscripts $i = 1, 2$), are shown in Figures 3(d) and (e), depicted by black and red lines, respectively. The horizontal dashed lines in Figure 3(e) indicate the scaling indices 5/3 and 1.4, and the latter corresponds to $\alpha_{\perp}$ within the TBL. The frequency breaks ($f_b$) estimated from PSDs, corresponding to ends of low-frequency fits within the windows $i$, are shown in Figure 3(f).

Figure 4. Temperature anisotropy $T_\perp/T_||$ vs. parallel plasma beta $\beta_||$ with instability thresholds for the event on 1998 September 1.

Let us consider now the possible sources of nonstationarity. To minimize the effects of nonstationarity, the fits were performed adaptively. The frequency ranges for the PSD fits were chosen so that the fits with the smallest errors were selected in each analyzing window. Figure 3(d) shows that the variations of $\alpha_{\perp}$ and the differences between the exponents for the two windows are much larger than the error bars (horizontal lines) of the fits. The largest differences between $\alpha_{hf1}$ and $\alpha_{hf2}$ occur when the angle $\eta(B, V)$ (Figure 3(b)) temporarily becomes less than $30^\circ$ between 1.34 and 1.37 UT. Similar differences are seen between 1.57 and 1.62 UT, when $\eta(B, V)$ changes from $\sim 25^\circ$ to $\sim 90^\circ$ across the flow boundary. These changes in $\eta$ are associated with directional changes of the mean $\langle B \rangle$ (not shown). Elsewhere, the variations of $\langle B \rangle$ are small.

Another source of nonstationarity is the temporal occurrence of pressure anisotropy. Figure 3(c) shows that the largest deviations in $\epsilon$ occur between 1.56 and 1.62 UT, overlapping in time with the largest changes in $\eta$. To further evaluate the impact of pressure anisotropies on magnetic fluctuations near the proton scale, we plot the proton temperature anisotropy ratio $T_\perp/T_||$ versus $\beta_||$ (Figure 4). The curves indicate thresholds for mirror mode, proton cyclotron, parallel, and oblique firehose instabilities (Hellinger et al. 2006). All the points inside the region bordered by instability thresholds correspond to stable situations with regard to temperature/pressure instabilities. The red and green points in Figure 4 are associated with the largest deviations of $\epsilon$ between 1.56 and 1.62 UT in Figure 3(c).

Sudden jumps in the data, e.g., shocks, discontinuities, and boundaries, can also lead to spurious scalings with $\alpha \sim 2$. In fact, this is the case near the left border of the outflow, where both $\alpha_{hf1}$ and $\alpha_{hf2}$ show values near 2, which are not associated with quasi-parallel population of $\eta < 30^\circ$ (Figure 3(b)). However, between 1.25 and 1.42 UT, we interpret the fluctuations in $\alpha_{hf1}$ as a combined effect of the jump at the left border of the outflow (possibly TD) and $\eta < 30^\circ$ within the analyzing windows. The frequency break points ($f_b$) within the same time interval seem to be unaffected by nonstationarities (Figure 3(f)). Nevertheless, $f_b$ changes from $\sim 0.3$ Hz to $\sim 1–1.5$ Hz when the spacecraft enters the TBL.
4. SPATIAL SCALES OF THE SPECTRAL BREAKS

The PSDs are estimated by excluding intervals containing sudden jumps, intervals of 3(⟨V⟩, V) < 30° or large deviations of ϵ. For the event on 1998 September 1 we found two time intervals, one within the reconnection outflow or flux tube, between 1.38 and 1.52 UT, and one within the TBL region, between 1.62 and 1.76 UT. Within these intervals the reduced PSDs are supposedly not distorted by other co-occurring physical processes. Repeating the same procedure, we found one more long enough reconnection boundary layer crossing interval in the database of Phan et al. (2009). This event occurred on 1998 March 25, between 16.2–16.6 UT. The structure of the TBL (not shown) is similar to the previous event.

Figure 5 shows the PSDs for both events. The bottom curve represents the only case for which the PSD is available within the space filling reconnection outflow (QSR model) or flux tube (TDR model). The scaling exponents are determined through a least-square fit with an error ±0.1 over the low frequencies and ±0.03 over the high frequencies. However, fluxgate magnetometers have limitations over the high frequencies, where the signal-to-noise ratio becomes low. Here we use a simple method to exclude the frequency ranges where noise dominates. The method is based on the comparison of finding the frequency break using two different approaches. The intercept of low-frequency and high-frequency power-law fits should result in the same frequency break as the high-frequency end point of a well-defined low-frequency fit. In Figure 5, the black circles correspond to the intercepts of two power-law fits and the red circles indicate the end points of the low-frequency fits. The frequency ranges dominated by noise can be eliminated from a fit by trying to get the black and red circles closer to each other.

Figure 5 shows that the low-frequency (inertial range) and the high-frequency (kinetic scale) fits give scaling indices \( a_{L} = 1.4–1.7 \) and \( a_{K} = 2.6–2.8 \), respectively. These values are in agreement with previous studies in which much longer time series were analyzed in the solar wind (Alexandrova et al. 2009; Bourouaine et al. 2012; Smith et al. 2006). In the spacecraft frame, the frequency break point, within the TBL, ranges between \( f_{b} = 0.8–1.5 \) Hz, which is different from \( f_{b} = 0.4 \) Hz, observed within the reconnection outflow. In the pristine solar wind, the break is usually observed at \( f_{b} = 0.2–0.4 \) Hz (Bourouaine et al. 2012; Smith et al. 2012).

Now we calculate and compare the local wavenumbers at proton scales supposing frozen in fluctuations in the solar wind. The wavenumber corresponding to the observed frequency break is \( k_{b} = 2πf_{b}/V \). The wavenumbers corresponding to proton Larmor radius \( k_{L} = 2πf_{c}/(V_{A} + V_{B}) \), inertial length \( k_{i} = 2πf_{p}/c \), and resonant Alfvénic damping \( k_{r} = 2πf_{p}/(V_{A} + V_{B}) \) were also calculated. Here \( V_{A} \) and \( V_{B} \) are the Alfvén and thermal speeds, \( c \) is the speed of light, and \( f_{c} \) and \( f_{p} \) are the cyclotron and plasma frequencies, respectively.

On 1998 September 1, inside the outflow \( k_{b}(\text{outflow}) = 0.0051 \text{ km}^{-1} \), within the TBL \( k_{b}(\text{TBL}) = 0.015 \text{ km}^{-1} \). We found \( k_{b}(\text{outflow}) = 0.0051 \sim k_{r} = 0.0058 < k_{L} \sim k_{i} = 0.013 \text{ km}^{-1} \) and \( k_{b}(\text{TBL}) = 0.015 \sim k_{L} \sim k_{i} \sim 0.014 > k_{r} = 0.007 \text{ km}^{-1} \). For the event on 1998 March 25, \( k_{b}(\text{TBL}) = 0.014 \sim k_{L} = 0.018 \sim k_{i} = 0.017 > k_{r} = 0.01 \text{ km}^{-1} \). The wavenumbers are determined by uncertainties of 10%–15%.

5. DISCUSSION AND CONCLUSIONS

We analyzed WIND data during crossings of reconnection outflow and outflow boundary structures in the solar wind. Two Petschek-type reconnection models were considered to explain the data: the TDR and the QSR models, leading to flux tube and space filling outflow structures, respectively (Figure 1). The models can explain the one-point measurements during the crossing of an unperturbed flow boundary (merged RD and slow shock or TD) and outflow equally well. For the outflow boundary embedded in a strongly fluctuating field and plasma regions, the TDR model predicts KH unstable TD with a developing turbulent vortex street behind the moving flux tube. For the same region, the QSR model predicts intense wave activity, turbulence, and instabilities within the outflow and separatrix layer. Although we could not distinguish between the predictions of two scenarios, we suggest that the fluctuations are driven by the reconnection outflow and form a unique TBL. The layer contains a slowly cooling–mixing plasma exhibiting a typical temperature–density profile with embedded significant directional changes of the magnetic field. The latter can correspond to turbulence generated structures, vortices, or current sheet.

In the reconnection database of Phan et al. (2009; 51 events between 1997 November and 2005 January), we found that 27 outflow events were accompanied by a boundary layer with embedded strong fluctuations. However, only two crossings were long enough for obtaining robust estimations of PSDs. Even if the crossings of turbulent regions were too short for the PSD calculations, these observations suggest that reconnection outflows can effectively generate fresh turbulence in the solar wind.

The PSDs indicate that, within the outflow and turbulent boundary regions, the observed scaling exponents over inertial and kinetic scales resemble those in the solar wind. Nonetheless, reconnection outflows can locally generate turbulence with different locations of the spectral breaks associated with different characteristic wavenumbers. The changes of wavenumbers imply different dissipation mechanisms near proton/ion scales. For example, the proton inertial length is of the order of turbulence-generated dissipation structures, current sheets (Dmitruk et al. 2004). The same spatial scale can also be associated by the Hall effect, which is able to steepen the PSDs (Galtier 2006).
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The Larmor radius can be associated with damping of kinetic Alfvén waves propagating at large angles relative to the local B (Leamon et al. 1998). The wavenumbers associated with resonant Alfvénic damping were recently observed in several high-velocity streams between 0.4 and 5 AU (Bruno & Trenchi 2014). Our results show that reconnection can determine the particular local field and plasma conditions, which may be in favor of one or another dissipation mechanism in the turbulent solar wind. This supports the recent results of Markovskii et al. (2008) that the spectral breaks or the dissipation wavenumbers in various data sets cannot always be interpreted in terms of one single universal mechanism in the solar wind.

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