THE COMPLEX STRUCTURE OF MAGNETIC FIELD DISCONTINUITIES IN THE TURBULENT SOLAR WIND

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Abstract

Using high-resolution Cluster satellite observations and a multi-dimensional intermittency technique, we show that the magnetic discontinuities in the turbulent solar wind are connected through the spatial scales, going from proton down to electron scales. In some circumstances, their structure resembles the Harris equilibrium profile in plasmas. Observations are consistent with a scenario where many current layers develop in turbulence and where the outflow of these reconnection events are characterized by complex sub-proton networks of secondary islands, in a self-similar way. Although in the past these pictures have been speculated to be separately ubiquitous, through theories and simulations, the present work confirms that “reconnection in turbulence” and “turbulent reconnection” coexist in space plasmas.

Key words: magnetic reconnection – solar wind – turbulence

1. INTRODUCTION

In the past decades, spacecraft observations suggested that plasma turbulence shares many similarities with classical hydrodynamics. The power spectrum of magnetic field fluctuations as a function of frequencies \( f \) manifests an inertial range, with a Kolmogorov-like scaling \( f^{-5/3} \) (e.g., Bruno \& Carbone 2013). More recently, high-resolution measurements revealed the presence of a secondary inertial sub-range, where the spectrum breaks down and exhibits a power index steeper than \(-5/3\) (Alexandrova et al. 2009; Sahraoui et al. 2009). The characteristic scales at which this breakdown occurs are given by the proton gyroradius \( r_p = v_{th,p} / \Omega_p \) (\( v_{th,p} \) being the proton thermal speed and \( \Omega_p \) the proton gyrofrequency) and/or the proton skin depth \( d_p = c / \omega_{cp} \) (\( c \) being the speed of light and \( \omega_{cp} \) the proton plasma frequency; Bale et al. 2005; Sahraoui et al. 2009; Narita et al. 2011). At these scales, the dynamics could be mediated by kinetic-Alfvén fluctuations, whistler-like perturbations, and coherent structures such as vortexes and current sheets (Osman et al. 2014).

The most narrow current sheets and filaments are present at electron scales, where turbulent energy eventually dissipates. This idea has been formulated implicitly in Perri et al. (2012) and Goldstein et al. (2015) and explicitly in Treumann \& Baumjohann (2015). However, the energy-dissipation mechanisms in a weakly collisional plasma such as the turbulent solar wind are far from being understood. Recent kinetic simulations clearly demonstrate that dissipation in turbulence takes place at filamentary electron-scale current sheets (Karimabadi et al. 2013; Haynes et al. 2014; Wan et al. 2015). Observations, however, are relatively ambiguous with respect to simulations because of measurement limitations (1D data spacecraft samplings). To elaborate a general picture of the processes that govern plasmas in the interplanetary medium as well as in laboratory experiments (e.g., Shaffner \& Brown 2015), it is therefore crucial to characterize the smallest scales with both observations and simulations.

One of the best candidates that may explain plasma energy dissipation on kinetic scales is magnetic reconnection, which implicates the change of topology of the magnetic field, with subsequent conversion of energy into flows, heat, and non-thermal effects. Usually, reconnection and turbulence have been studied as separate topics, but more recently it has been suggested that these effects may coexist (Servidio et al. 2009; Osman et al. 2014; Zank et al. 2014; Goldstein et al. 2015). Namely, reconnection of thin current sheets can take place in magnetohydrodynamics, as well as in plasma-kinetic models (Karimabadi et al. 2013). On a parallel path (Matthaeus \& Lamkin 1986; Lazarian \& Vishniac 1999), it has been proposed that the process of magnetic reconnection can be very efficient when turbulence develops “inside” the above thin current sheets. At very high Reynolds number, in fact, it is expected that these narrow current layers become unstable, generating micro-plasmoids and secondary islands in a self-similar way (Lapenta 2008; Samtaney et al. 2009).

Here, we investigate the coexistence of reconnection and turbulence in the space plasmas, inspecting the solar wind from large to small scales. The results obtained merge the picture of “reconnection-in-turbulence,” where large-scale energy containing structures reconnect producing layers at scales on the order of the proton skin depth, with the picture of “turbulent reconnection,” where turbulence develops inside the outflows of the above current sheets, at scales on the order of (and much smaller than) the proton skin depth.

2. DATA ANALYSIS AND RESULTS

The data analyzed are taken in the pristine, undisturbed solar wind from the Cluster 4 spacecraft on 2007 January 20, 12:00–14:00 UT. Following Yordanova et al. (2015), the FGM and the STAFF search coil data in burst mode (sampling frequencies 67 and 450 vec s\(^{-1}\), respectively) are combined by low-passing FGM data and high-passing STAFF data using a cutoff frequency of 1 Hz. In this sampling, the solar wind bulk speed is \( V_w \approx 600 \text{ km s}^{-1} \), and the mean magnetic field (averaged over the entire data set) is \( B_0 \approx 4 \text{ nT} \) (see also Table 1 in Yordanova et al. 2015). In terms of characteristic plasma scales, the proton Larmor radius is \( \rho_p \approx 193 \text{ km} \), the proton inertial length \( d_p \approx 163 \text{ km} \), the electron Larmor radius \( \rho_e = v_{th,e} / \Omega_e \approx 3.67 \text{ km} \), and the electron inertial length \( d_e = c / \omega_{ce} \approx 3.75 \text{ km} \), where \( v_{th,e} \) is the electron thermal speed, \( \Omega_e \) the electron gyrofrequency, and \( \omega_{ce} \) the electron plasma frequency.
The magnetic field power spectral densities (PSDs) of the magnetic field components in Geocentric-Solar-Ecliptic (GSE) reference frames are shown in Figure 1. They have been calculated using the square of wavelet coefficients at different timescales. The STAFF noise level (magenta line) is also shown and indicates that at frequencies \( \geq 50 \) Hz the signal-to-noise ratio becomes comparable. The power spectral density of the magnetic field shows a characteristic behavior of solar wind turbulence. At frequencies lower than \( \sim 10^{-3} \) Hz, corresponding to a characteristic time of about 20 minutes, the spectrum becomes almost flat, indicating the typical large-scale decorrelation. This first spectral break roughly indicates the correlation scale of turbulence, characterized by large-scale structures. At higher frequencies, between \( 10^{-2} \) and 0.3 Hz, the typical inertial range of the solar wind is observed, with a power law close to the Kolmogorov prediction for hydrodynamics, namely, \( \text{PSD}(f) \sim f^{-5/3} \). Here, we found a little shallower index, namely, \( \sim f^{-1.5 \pm 0.02} \), pretty usual in the solar wind since the selected interval corresponds to fast wind. A well-defined spectral break at \( \sim 0.5 \) Hz is observed, separating the above Kolmogorov-like inertial range, with a secondary inertial range where the spectrum is steeper, with an exponent \(-2.9 \pm 0.5\). The change in the slope of the power spectrum at frequencies higher than the proton gyrofrequency indicates a change in the nature of the turbulent cascade with possible plasma-kinetic effects at work (Alexandrova et al. 2013). The characteristic frequency at which the spectral break is observed is close to both the Doppler shifted proton gyroradius \( f_{\rho p} = \frac{V_{sw}}{2\pi \rho_p} \) and the proton inertial length \( f_{d_p} = \frac{V_{sw}}{2\pi d_p} \), where \( \rho_p \) and \( d_p \) are the proton Larmor radius and the proton inertial length defined before, respectively. Note, however, that it is not clear whether the breaking frequency is due to Larmor radius or to proton skin depth effects (Telloni et al. 2015).

At the highest frequencies, for \( f > 20 \) Hz, we observe a further change of behavior in the cascade, where the behavior can be either power-law type or exponential, as discussed in Sahraoui et al. (2009) and Alexandrova et al. (2009). These electron characteristic frequencies, \( f_{\rho e} = \frac{V_{sw}}{2\pi \rho_e} \) and inertial lengths \( f_{d_e} = \frac{V_{sw}}{2\pi d_e} \), are reported as full vertical lines in Figure 1, and they are extremely close. Note that the applicability of the Taylor hypothesis can be problematic at very high frequencies, namely, for \( f \gg f_m \), where the dynamics of the fluctuations can be quite fast. However, as we will show below, here we identify singular structures, which are consistent with equilibrium-like solutions in plasmas, and therefore with zero-frequency modes. For these identified current layers, the hypothesis is likely to be satisfied (for more details on the validity of the Taylor hypothesis, see, e.g., Brown et al. 2015). Besides the spectral properties, plasma turbulence is spatially characterized by intermittent structures bursty in space (Veltri 1999; Bruno et al. 2001; Kiyani et al. 2009; Perri et al. 2012). These structures can be classified in several ways (Veltri et al. 2005), but they are generally strong inhomogeneities of the magnetic field (Burlaga & Ness 1968; Tsurutani & Smith 1978). To trace these abrupt spatial changes of the magnetic field, we use the Partial Variance of Increments (PVI), which measures the "spikiness" of the signal relative to a Gaussian value and is directly connected to the intensity of the current (Donato et al. 2013). The PVI time series is defined in terms of the magnetic field increment vector \( \Delta \mathbf{B}(t, \tau) = \mathbf{B}(t + \tau) - \mathbf{B}(t) \) (Greco et al. 2008):

\[
\text{PVI}(t, \tau) = \frac{|\Delta \mathbf{B}(t, \tau)|}{\sqrt{\langle |\Delta \mathbf{B}(t, \tau)|^2 \rangle}}
\]

where the average is over a suitably large trailing sample computed along the time series and \( \tau \) is the time lag. For this study we compute PVI on inertial scales from \( \tau = 15 \) to 1 s, and on kinetic sub-proton scales ranging from \( \tau = 0.7 \) to 0.022 s. The smallest time separation used corresponds to a frequency of 45 Hz, where the signal-to-noise ratio is still high (see Figure 1). The PVI series, computed for \( \tau = 0.022 \) s, is reported in Figure 2(a) for a portion of the data set. The signal, as it can be seen, displays a strongly intermittent character, typical of turbulence. A similar behavior, in a different setting (Earth’s magnetosheath), at scales larger than the one analyzed here, has been observed in Chasapis et al. (2015).

In order to characterize the most abrupt events, a set of structures with PVI amplitude above a given threshold can be

Figure 1. Power spectral density (PSD) of the magnetic field. The spectral slopes of the inertial range and of the high-frequency range are displayed. Characteristic plasma frequencies are reported with vertical lines (see the text). Full (magenta) line is the STAFF search coil noise level.
defined. We did not find any preferential orientation of these identified discontinuities with respect to the Parker spiral (that forms an angle of about 70° with the GSE x direction at 1 au).

Once these structures have been localized, the magnetic field (depleted by the average component) has been rotated in the local minimum variance reference frame, defined by the basis \(\hat{B}, \hat{m}, \hat{n}\). As reported in Figure 2(b), \(\hat{B}\) is the unit vector along the maximum. In this reference frame, it is interesting to see the local topology, identifying whether these are current layers. We further estimate the current density vector \(\mathbf{J} = \nabla \times \mathbf{B}/\mu_0\) within those structures. From a single-satellite sampling, the only two components of \(\mathbf{J}\) that can be estimated are \(J_x\) and \(J_z\) (multispacecraft techniques are not applicable in this analyzed period). These components have been computed via the magnetic field differences along the GSE x direction, in the limit of small \(\tau\). Structures showing the minimum variance axis \(\hat{n}\) almost parallel to \(x\) axis have been selected. First, we impose that the angle between \(\hat{n}\) and \(x\) is \(\alpha < 8^\circ\). Second, we restrict to layers with the minimum variance component \(B_n \sim B_m \sim 0\). This configuration restricts the analysis of the current to the cases reported in the cartoon of Figure 2(b). These constraints ensure that the above surrogate computed from the Cluster 4 data is very close to the actual current density.

The current layers detected by the PVI method under the above constraints seem to have a self-consistent shape at time lags that range from inertial to sub-proton scales, resembling equilibrium solutions of both fluid-like and kinetic plasmas. The simplest analytical model that could represent thin current layers on kinetic scales is the well-known Harris sheet (Harris 1961), which is widely used to describe a plasma sheath confined between two regions of oppositely directed magnetic field. It is a kinetic equilibrium and the earliest exact analytical solution of the Vlasov equation. Under some assumptions, the magnetic field follows a 1D hyperbolic-tangent profile. The number of structures selected by PVI ranges from thousands \((\tau = 0.022\ s)\) to hundreds \((\tau = 1\ s)\). Applying the geometrical restrictions of the minimum variance analysis described above, we found that the Harris profiles well describe 5% and 10% of the discontinuities. Figure 3 shows two examples of such 1D current sheets in their local minimum variance reference frame. The time duration is \(\Delta \tau \sim 0.1\ s\) (a) and \(\Delta \tau \sim 0.7\ s\) (b), which correspond to 60 km and 420 km along \(x\), respectively, assuming the validity of the Taylor frozen-in hypothesis. The maximum variance component \(B_t\) performs a smooth, large-amplitude rotation, while \(B_m \sim B_n \sim 0\). Note that \(B_m\) albeit very small, displays a multipolar signature, typical of solar wind reconnection exhausts (Eriksson et al. 2015). \(B_t, B_m,\) and \(B_n\) refer to the fluctuating part of the magnetic field after that the mean value, computed on the time duration of the discontinuity, is subtracted. For the above structures, the direction of the removed average field is almost aligned to \(\hat{m}\) and perpendicular to \(\hat{l}\). Moreover, the full magnetic field component along \(\hat{m}\) is constant and equal to the removed average field over the interval so that the geometry corresponds to that of a common Harris sheet + guide field, as reported pictorially in Figure 2(b).

The best fits from the Harris model \(B = B_0 \tanh(x/\lambda)\), where \(x = V_m t\) and \(\lambda\) is the half-thickness of the layer, are also compared in the same figures (thick lines), indicating very good agreement with the plasma equilibrium theory. The value of \(\lambda\) is \(\sim 3d_e\) for the current sheet on the left and \(\sim 55d_e\) for that on the right. The partial estimation of \(J_x\) and \(J_z\) can be then converted into a full characterization of one component when the system is rotated in minimum variance frame, whose magnitude is shown in the bottom panels of Figure 3 for the same structures. Here, we compare the profile with the Harris expectation \(J \sim (B_0/\lambda) \cosh^{-2}(x/\lambda)\).

The values of the reduced \(\chi^2\) for the two examples are \(\chi^2 = 0.0045\) and \(\chi^2 = 0.02\), respectively. Note that only high-cadence measurements are capable to give such unambiguous profiles. To verify the validity of the Harris solution, we performed a test, fitting the profiles with sinusoidal functions (as, for example, it would be for wave-like activity). For the current profiles in panels (c) and (d) of Figure 3, using \(\cos(x/\lambda)\), we obtained a less precise fit with \(\chi^2 = 0.01\) and \(\chi^2 = 0.05\), respectively.

From a detailed inspection of our data set, we found that such Harris profiles persist from inertial down to electron scales in a self-similar way. In order to quantify this cross-scale connection, we performed a multi-dimensional intermittency analysis, computing the full PVI as a function of both scales and positions in time. Figure 4 represents this “scalogram” of the PVI series, taken in a sub-interval of the original data set. The duration of this sub-interval is about 11 s that corresponds to \(\sim 40\) proton inertial lengths \(d_p\). A time lag \(\tau = 15\ s\) corresponds to \(\sim 55\ d_p\) and \(\tau = 0.022\ s\) to \(\sim 0.08\ d_p\). The two-dimensional contour clearly shows high values of PVI (current) at large scales that connect down to kinetic scales, at wavelengths smaller than the proton skin depth. This connection is very interesting and somehow complex, being a ubiquitous manifestation of intermittency in plasma turbulence. The most interesting feature of the plot is the “ramification” of the current, following large-scale shears, going down to kinetic scales: discontinuities on the order of the proton skin depth (or bigger) seem to “break up” into smaller sub-proton structures. These nested structures are characterized by high values of the current and might be related to substructures of outflow layers, as we will investigate below. Some of these are the 1D current sheets depicted in Figure 3; some others may be different types of structures, not reminiscent of any Harris profiles. In the turbulent solar wind, the satellite can encounter several
structures. We define connected discontinuities (daughters) when multiple connections exist, while they are isolated if they are connected only to themselves. An example of this genealogical tree is reported in Figure 5(b), showing networks (hierarchical clusters) and singular structures. At the short timescales, we found 1245 discontinuities, 617 of which are connected, and 628 are isolated. This percentage, about 50%, has been found to be weakly dependent on the threshold.

The above analysis suggests that many of the discontinuities are nested into large-scale current layers (in agreement with the picture of turbulent reconnection), while others are small-scale isolated structures. The latter can be either single isolated layers or can be connected to larger discontinuities that are not on the line of sight of the satellite (i.e., exhausts that are in other positions not detected from the satellite) or even be regions that are closer to the reconnecting electron layer (X-point for 2D reconnection). Finally, we would like to point out that some of these layers can be also related to other processes that do not involve magnetic reconnection at all.

The above scenario is further supported by numerical works. As reported in accurate simulations of magnetic reconnection (Daughton et al. 2011; Lapenta et al. 2015), the structure of the outflows is very complex, where different current layers, plasmoids, and secondary current sheets are formed. Inside this structure, indeed, one can detect several secondary X-points, where reconnection is occurring in a self-similar way. In the above models of turbulent reconnection, where the turbulent outflows contain reconnection and vice-versa, it is pretty clear that the signal of PVI would manifest a tree-like structure (observed here), where many macro-current layers can be captured with our cross-scale technique and where these layers proliferate into micro-reconnecting sheets at the electron skin depth. Obviously, when the scales approach the electron skin depth, contacting fields of opposite direction may reorganize, locally annihilating the anti-parallel components and finally providing energy for direct plasma heating and particle/plasma acceleration (Karimabadi et al. 2013). In this case, reconnection may become very fast proceeding on electron plasma timescales (Treumann & Baumjohann 2015).
3. CONCLUSIONS

In summary, using Cluster high-resolution data, we investigated the structure of thin current sheets that populate the turbulent solar wind. The following picture emerges for the solar wind: the turbulent cascade naturally forms current sheets at several scales, down to the proton skin depth. Approaching smaller scales, a current “fragmentation” process arises, producing, in some cases and constraints (e.g., the constraint on the particle pressure needs to be satisfied at the same time), Harris-like layers down to scales comparable with the electron skin depth. This process of multiplicative generation of discontinuities/layers, suggested in the past years by a number of numerical simulations (Lapenta 2008; Daughton et al. 2011; Karimabadi et al. 2013; Haynes et al. 2014; Lapenta et al. 2015; Wan et al. 2015), as well as by more theoretical works (Matthaeus & Lamkin 1986; Lazarian & Vishniac 1999; Veltri 1999; Treumann & Baumjohann 2015), is observed here for the first time in space. Possible turbulent reconnecting sites are identified with the use of a cross-scale intermittency analysis, where complex outflows are produced. From the observations presented in this work, it is intuitive to think that, once the current eddy filaments approach the electron inertial scale, magnetic reconnection might play an important role in the final dissipation process of turbulence. This picture needs to be reconciled with observations of the saturation of the scale-dependent kurtosis at sub-proton scales (Kiyani et al. 2009; Leonardis et al. 2016). However, we would like to point out that magnetic reconnection is not the only possible process that is occurring in turbulence, but other local extreme events might mediate the dissipation mechanisms, such as vortex-like formations, small-scale flux ropes, and compressive shock like structures as well as wave-like kinetic damping.

An equally important pressure counterpart is needed to fulfill the theoretical picture that connects local Harris equilibria, reconnection, and current-formational processes. Future improvements offered by the high-resolution observations from the next generation of spacecraft will reveal the full complex nature for the termination of the turbulent cascade in plasmas. In particular, as suggested in Hesse et al. (2001), these thinnest current layers may become the main sites of heating, where electron temperature is higher than the surrounding ambient, and where electron contributions in the Ohm’s law become the dominant terms. In the vicinity of the electron region outflows, there is compelling evidence that the electron velocity distribution function becomes highly distorted, producing temperature anisotropy, agyrotropy, and resonance effects (Haynes et al. 2014). Even if globally the particle mean free path is very long, in these regions because of the above strong distortions, it can be that collisions might play a local role, converting irreversibly the turbulent energy cascade into heat. The concepts of reconnection-in-turbulence, where many sites are produced by turbulence, and turbulent reconnection, where reconnection generates turbulent outflows, are found here to be two synergistic processes of space plasmas. In the future, we plan to extend our study, comparing simulations and larger data sets.

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