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# Are there current-sheet-like structures in the Earth's magnetotail as in the solar wind – results and implications from high time resolution magnetic field measurements by Cluster

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**Abstract.** Recent studies of solar wind MHD turbulence show that current-sheet-like structures are common in the solar wind and they are a significant source of solar wind MHD turbulence intermittency. While numerical simulations have suggested that such structures can arise from non-linear interactions of MHD turbulence, a recent study by Borovsky (2006), upon analyzing one year worth of ACE data, suggests that these structures may represent the magnetic walls of flux tubes that separate solar wind plasma into distinct bundles and these flux tubes are relic structures originating from boundaries of supergranules on the surface of the Sun. In this work, we examine whether there are such structures in the Earth's magnetotail, an environment vastly different from the solar wind. We use high time resolution magnetic field data of the FGM instrument onboard Cluster C1 spacecraft. The orbits of Cluster traverse through both the solar wind and the Earth's magnetosheath and magnetotail. This makes its dataset ideal for studying differences between solar wind MHD turbulence and that inside the Earth's magnetosphere. For comparison, we also perform the same analysis when Cluster C1 is in the solar wind. Using a data analysis procedure first introduced in Li (2007, 2008), we find that current-sheet-like structures can be clearly identified in the solar wind. However, similar structures do not exist inside the Earth's magnetotail. This result can be naturally explained if these structures have a solar origin as proposed by Borovsky (2006). With such a scenario, current analysis of solar wind MHD turbulence needs to be improved to include the effects due to these curent-sheet-like structures.

**Keywords.** Interplanetary physics (MHD waves and turbulence; Solar wind plasma) – Magnetospheric physics (Magnetotail)

## 1 Introduction

Solar wind provides us a great opportunity to study magnetohydrodynamic (MHD) turbulence in a collisionless plasma. Since 1960s, a great amount of work on MHD turbulence has been performed by many workers (see Tu and Marsch, 1995; Goldstein et al., 1995; Bruno and Carbone, 2005, for extensive reviews). The MHD turbulence bears many similarities to its hydrodynamic sibling which was studied first by Kolmogorov (1941) (hereafter K41 theory), but differs in many aspects due to the presence of a strong magnetic field (Iroshnikov, 1963; Kraichnan, 1965; Biskamp, 1993). In the past several decades, the launches of multiple spacecraft, noticeably Voyager, Helios, WIND, Ulysses and Cluster, have accumulated a significant amount of data on plasma density $\rho$, flow speed $\boldsymbol{U}$, and magnetic field $\boldsymbol{B}$ with a resolution that is not available in terrestrial laboratories. These data have revealed valuable information about solar wind MHD turbulence and its dynamical evolution.

A central topic of the solar wind MHD turbulence that is gaining more attention is intermittency. In a collisionless plasma such as the solar wind, intermittency arises because the fluctuations of magnetic field and fluid velocity are not scale invariant as conjectured in the K41 theory. Roughly speaking, intermittency reflects how turbulence is unevenly distributed in space. Mathematically, intermittency describes how a structure function $S_q^p(l)$ varies with the order $p$. Here $S_q^p(l)$ is the $p$-th order structure function defined for a physcial quantity $q$ ($q$ can be, e.g., $v_{||}$ or $B$) through,

$$S_q^p(l) = < |q(x) - q(x+l)|^p > \approx l^{\zeta_p}. \quad (1)$$

In the above, the quantity $\zeta_p$ is the scaling exponent of $S_q^p(l)$ and is in general a function of $p$. In the absence of intermittency, $\zeta_p = p/m$ where $m$=3 and 4 for normal fluid and magnetofluid, respectively. Any deviation from this linear dependence indicates the presence of intermittency.

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In the context of solar wind MHD turbulence, the first study of intermittency was done by Burlaga, in a series of papers (Burlaga, 1991a,b,c), Burlaga, using Voyager data at various heliocentric distances, showed that the $\zeta_p$ associated with fluctuating solar wind speed is not linear with $p$. Later, Marsch and Liu (1993) analyzed Helios data in the inner heliosphere and showed that not only intermittency exists in the solar wind, but its strength can also differ much depending on plasma properties: small scales are more intermittent than large scales and slow wind is more intermittent than fast wind. Since the work of Marsch and Liu (1993), studies on the intermittent character of solar wind have been widely reported (e.g., Marsch and Tu, 1994, 1997; Carbone et al., 1995a,b; Ruzmaikin et al., 1995; Tu and Marsch, 1996; Horbury et al., 1996, 1997; Bruno et al., 1999, 2001, 2003, 2004; Veltri et al., 2005; Salem et al., 2007). Among these, Ruzmaikin et al. (1995) attempted to relate intermittency with specific solar wind turbulence models. They showed that if one reduces the measured spectral index of magnetic field fluctuations by an amount governed by the intermittency scaling exponent, then the reduced power spectral index yields a scaling agreeing with the random-phase Alfvénic turbulence model of Kraichnan (1965) for magnetofluid. Attempts to include the effects of intermittency in solar wind turbulence model have also been reported by Tu and Marsch (1996), who tried to integrate the $p$-model of Meneveau and Sreenivasan (1987) to the Tu (1988) model of a developing turbulence. Clearly, these works suggested that a good understanding of the solar wind intermittency is necessary for a good understanding of solar wind turbulence.

A very important intermittent structure in the solar wind is current sheet. A current sheet is a 2-D structure where the magnetic field direction changes significantly from one side to the other. Recently, Veltri and Mangeney (1999) examined magnetic field and fluid velocity data from ISEE space experiment and found that the current sheet is a major source for solar wind MHD turbulence intermittency. Using a Haar wavelets technique, Veltri and Mangeney (1999) calculated power spectra and structure functions for a time range between 1 min to about 1 day. Their results showed that in solar wind (a magneto-fluid) the most intermittent structures are current sheets where magnetic field rotates by an angle of about 120–130 degrees. This differs from ordinary fluids where the most intermittent structures are two-dimensional vortices. In a related study, using Helios 2 data at 0.9 AU, Bruno et al. (2001) performed a minimum variance analysis to study how the solar wind magnetic field vector evolves for several selected time periods. By plotting the trajectory of the tip of the magnetic field vector in the minimum variance reference system, Bruno et al. (2001) showed that the magnetic field direction at times undergo abrupt changes, implying the presence of current sheet. Besides trying to identify current sheet in the solar wind, Veltri and Mangeney (1999) also pointed out that by using a conditional sampling scheme, one can eliminate the intermittency effects in the power spectra of the turbulence, thus providing a possible distinguishment of nonlinear cascade of Kolmogorov type from Kraichnan type in the solar wind. Clearly, to properly discern which cascading is taking place, identification of current sheet in the solar wind is crucial.

While the analyses of Veltri and Mangeney (1999), Veltri et al. (2005) and Bruno et al. (2001) suggested that current sheet can be quite common in the solar wind, the orgin of it is still puzzling. On the one hand, numerical MHD simulations by Zhou et al. (2004) showed that nonlinear interactions in the solar wind can lead to the generation of current sheet; similarly study by Chang et al. (2004) also showed that starting from an isotropic initial condition, non-linear interactions in the solar wind can naturally lead to the emergence of various coherent structures, including current sheet. On the other hand, Borovsky (2006), on examining one-year worth magnetic field data from ACE spacecraft, has suggested that these current sheets could be "magnetic walls" of flux tubes in the solar wind and they are the relic structures in the solar wind which can be traced back to the surface of the Sun as the boundaries of supergranules. Because they are boundaries of supergranules, they separate solar wind plasmas into various distinct regions. In this picture, current sheets are carried out by the solar wind and the plasma in the solar wind are bundled in "spaghetti-like" flux tubes with granules being the footpoints on the surface of the Sun. We note that the concept of flux tube is an old idea. It has been first proposed some 40 years ago as an attempt to explain the modulation of cosmic rays by Bartley (1966) and McCracken and Ness (1966) and later was adopted by Mariani et al. (1973) to explain the observed variations in the occurrence rate of discontinuities in interplanetary magnetic field.

The suggestion of (Borovsky, 2006) is particularly interesting in that it conjectures that many (if not all) current sheets in the solar wind are relic structures in the solar wind, not generated by non-linear interactions such as shown by Zhou et al. (2004). If this is indeed the case, then these flux tubes will introduce an extra source of intermittency which is not intrinsic to the solar wind MHD turbulence. Clearly, to obtain a proper understanding of the solar wind MHD turbulence, it is important to separate this extra source of intermittency from those that are intrinsic of the solar wind turbulence which are caused by non-linear interactions. In this work, as an attempt to identify the origin of current sheet in the solar wind, we perform a detailed data analysis to answer a related question: "are there similar current-sheet-like structures in another mangetofluid that differs from the solar wind?" In particular, we ask "are there current-sheet-like structures like those in the solar wind in the Earth's magnetotail?" Obviously, if such current-sheet-like structures do exist in the Earth's magnetotail where no supergranule boundaries can be identified, then these structures are most likely generated by non-linear interactions of MHD turbulence and the suggestion of (Borovsky, 2006) is doubtful. If, however, no such current-sheet-like structures are found in the

Earth's magnetotail, then what Borovsky (2006) suggested could be correct. Of course, failing to find current-sheet-like structures by itself does not necessarily prove the correctness of the Borovsky (2006) proposal. It could be very possible that because the plasma environments of the solar wind and the Earth's magnetotail are vastly different, current sheet-like structures do not easily develop in the Earth's magnetotail although other types of intermittent structures may emerge Chang (1999).

To answer the question of "are there similar current-sheet-like structures in another mangetofluid that differs from the solar wind?", we perform in this work, the same data analysis in both the solar wind and the Earth's magnetotail using data from the same instrument onboard Cluster C1. By restricting ourselves to using data from Cluster C1 only, we ensure that our analysis is error-free from using different instruments. Our analysis is based on a newly developed procedure reported in (Li, 2007, 2008). This technique makes use of high time resolution magnetic field data and can be used to effectively identify current-sheet-like structures in a plasma. For our analysis, we use magnetic field data from Cluster C1 spacecraft. The orbits of Cluster traverse through both the solar wind and the Earth's magnetosheath and magnetotail, making its dataset the most suitable for our study.

In the following, we first briefly discuss the technique used in (Li, 2007, 2008) in Sect. 2. We then present our period selection and the corresponding data analysis in Sect. 3. We conclude in Sect. 4.

## 2 Current sheets and $\zeta$-scaling of $F(\theta, \zeta)$

To examine the existence of flux-tube-like structures in the solar wind, Li (2007, 2008) introduced a systematic data analysis procedure. This procedure consists of two steps. The first step is a statistical study, allowing one to verify the existence of these structures. The second step can be used to locate the exact locations of individual current sheets. Here we briefly outline the first step of the procedure, which is most relevant to this study.

Consider a time series of magnetic field data $\boldsymbol{B}(t_i)$ where $i$=1, 2, ....$N$ are time indices. One can define a tensor $R(\zeta)$,

$$R_{\alpha,\beta}(\zeta) =< \hat{b}_\alpha(t)\hat{b}_\beta(t+\zeta) > \tag{2}$$

where $\alpha$ and $\beta$ are two Cartesian indices in any orthogonal coordinate system, for example, the Inertial Heliographic coordinate system (IHS) and $\hat{b}=\boldsymbol{B}/B$ is the unit magnetic field vector. Taking the trace of $R(\zeta)$, one obtains a coordinate independent quantity (Li, 2007),

$$Tr[R(\zeta)] =< \hat{b}(t) \cdot \hat{b}(t+\zeta) > . \tag{3}$$

Clearly, $Tr[R(\zeta)]$ is the ensemble average of the cosine of the angle between $\hat{b}(t)$ and $\hat{b}(t+\zeta)$. If we now define the probability density of finding an angle between $\hat{b}(t)$ and $\hat{b}(t+\zeta)$ within $\theta$ and $\theta+\delta\theta$ to be $f(\theta,\zeta)$, then we have,

$$< \hat{b}(t) \cdot \hat{b}(t+\zeta) >= \int f(\theta,\zeta) \cos\theta d\theta. \tag{4}$$

Using the magnetic field data, $f(\theta,\zeta)$ can be computed through,

$$f(\theta,\zeta)\Delta\theta = \frac{N^\zeta(\theta < \theta' < \theta + \Delta\theta)}{N^\zeta(0 < \theta' < \pi)}. \tag{5}$$

Here $N^\zeta(\theta<\theta'<\theta+\Delta\theta)$ is the number of measurement pairs where the angle between $\hat{b}(t)$ and $\hat{b}(t+\zeta)$ is within the range of $(\theta, \theta+\Delta\theta)$ and $N^\zeta(0<\theta'<\pi)$ is the total number of measurements. If the total time period is $T$ and the time resolution of the data is $\delta$, one can show that,

$$N^\zeta(0 \le \theta \le \pi) = (T-\zeta)/\delta \approx T/\delta. \tag{6}$$

where we assumed $T \gg \zeta$ ($T\sim$ a day and $\zeta\sim$ minutes). Hence $N^\zeta(0\le\theta\le\pi)$ is independent of $\zeta$. We next define the integrated distribution function $F(\theta,\zeta)$ through,

$$F(\theta,\zeta) = \int_\theta^\pi d\theta' f(\theta',\zeta) = \frac{N^\zeta(\theta < \theta' < \pi)}{N^\zeta(0 < \theta' < \pi)}. \tag{7}$$

Clearly $F(\theta,\zeta)$ represents the frequency of having the measured angle larger than $\theta$.

The essence of the method introduced in (Li, 2007, 2008) to identify current sheets in the solar wind is the following: if there are magnetic walls separating plasma into individual flux tubes where the magnetic field directions change significantly between adjacent flux tubes, then the quantity $N^\zeta(\theta<\theta'<\pi)$ and consequently the integrated distribution function $F(\theta,\zeta)$ shall scale linearly with the time separation $\zeta$ when $\theta$ is larger than some critical angle $\theta_0$, i.e.,

$$F(\theta, N\zeta) \sim NF(\theta,\zeta) \qquad \text{when} \quad \theta > \theta_0. \tag{8}$$

On the contrary, if no such a wall exists in the data, then the scaling law of Eq. (8) does not hold.

Using magnetic field data from Ulysses spacecraft, (Li, 2007) found that the scaling law of Eq. (8) does indeed exist in the solar wind. Furthermore, current sheets seem to be ubiquitous in the solar wind. It exists in both solar maximum and solar minimum, at high latitude (fast wind) and near ecliptic plane (slow wind), near 1 AU and as far as 5 AU. This ubiquity can be explained by either (A) current sheets being the magnetic walls of flux tubes, which are relic structures of granules on the solar surface or (B) current sheets being a common intermittent structure of MHD turbulence arising naturally due to non-linear interactions. Of course, (A) and (B) are not mutually exclusive and both can contribute. To better understand the origin of flux tubes in the solar wind, it is necessary that we examine plasmas that are different from solar wind. For this purpose, planetary magnetospheres and in particular, Earth's magnetosphere is our best candidate. In the next section, we discuss our data analysis using magnetic field data in both the solar wind and Earth's magnetotail from Cluster spacecraft.

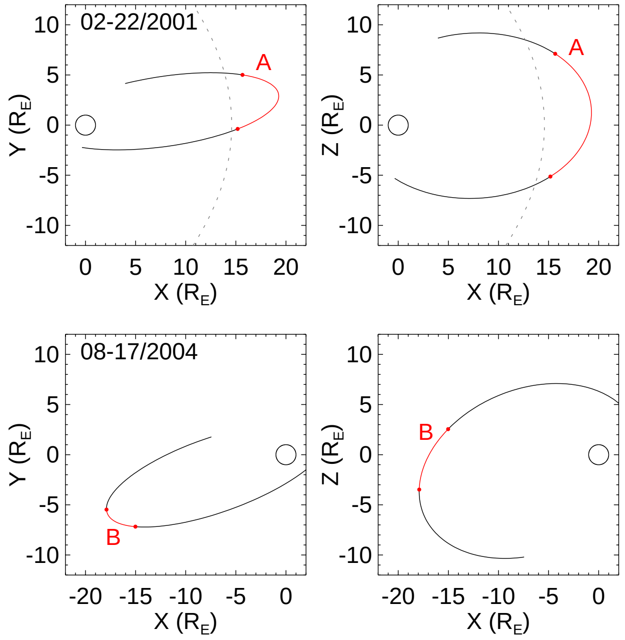

**Fig. 1.** Cluster orbits projected onto the x-y and x-z planes during the time period selected in this study. The upper panel shows the orbit when the Cluster was in the solar wind on 22 February 2001 (period A), and the lower panel in the magnetotail on 17 August 2004 (period B). The line segments marked by red color indicate the time periods selected in this study. In the upper panel the bow shock location is shown as the dashed line.

## 3 Data analysis and results

For our study, we use magnetic field data from the Flux Gate Magnetometer (FGM) on-board spacecraft Cluster C1 (Balogh et al., 2001). Although Clsuter mission consists of multiple spacecraft, we use data from Cluster C1 only. This is to ensure our analysis is error-free from using multiple instruments/spacecraft. FGM on-board Cluster C1 has a high time resolution of 22.5 Hz (in this study we use data with a 5 Hz resolution). A time resolution as high as 5 Hz guarantees enough data points for a relatively short period, crucial for our study as Cluster C1 only spends ∼1 day in the solar wind and/or Earth's magnetotail at a time.

We examine the magnetic field data for two time periods, one in the solar wind and the other inside Earth's magnetotail. The two periods selected for this study are shown in Fig. 1. Period A corresponds to the whole day 053 of 2001; during this period Cluster C1 is in the solar wind. Period B corresponds to day 229 of 2004, from 06:00 to 16:00; during this period Cluster 1 is in the Earth's magnetotail. Note that in selecting period A, it is important to ensure that the influence from the Earth's bow shock is minimized. This is because at the parallel portion of the Earth's bow shock, wave activities, in particular ULF waves are commonly observed. To ensure our data are free from contaminations of wave activities, we require period A to be in the perpendicular portion of the bow shock.

The results of our analysis are shown in Figs. 2 and 3. Figure 2 plots $F(\theta,\zeta)$ as function of $\theta$. The upper panel is for period A, when Cluster C1 is in the solar wind; the lower panel is for period B, when Cluster C1 is inside Earth's magnetotail. In both panels, solid black curves are for $\zeta=20$ s, solid red curves for $\zeta=40$ s, solid blue curves for $\zeta=60$ s, solid magenta curves for $\zeta=80$ s, dash black curves for $\zeta=100$ s, dash red curves for $\zeta=100$ s, and dash blue curves for $\zeta=140$ s. From the figure, we find that $F(\theta,\zeta)$ for different $\zeta$s for period A are nicely ordered with respect to $\theta$. Furthermore, when $50^\circ<\theta<90^\circ$, curves for different $\zeta$s are parallel to each other. As will be shown in the next figure, this parallel behavior reflects a linear dependence of $F(\theta,\zeta)$ on $\zeta$, a strong evidence for the existence of flux tubes in the solar wind (Li, 2007, 2008). In contrast to this nice ordering of $F(\theta,\zeta)$ for period A, $F(\theta,\zeta)$s for period B show no clear $\zeta$ dependence. Indeed, at some large $\theta$s ($>85^\circ$), $F(\theta,\zeta)$ for a larger $\zeta$ (e.g., 140 s) can be even smaller than $F(\theta,\zeta)$ for a smaller $\zeta$ (e.g., 80 s), exhibiting no scaling on $\zeta$.

Figure 3 plots $F(\theta,\zeta)$ as a function of $\zeta$. The upper panel is for period A and the lower panel for period B. In both panels, four $\theta$ values, 50° (red), 60° (blue), 70° (purple) and 80° (orange) are plotted. Each curve contains data points from a total of 15 $\zeta$'s. For period A (i.e., in the solar wind), the linear dependence of $F(\theta,\zeta)$ on $\zeta$ is easily seen. For period B (i.e., within the Earth's magnetotail), no linear dependence of $F(\theta,\zeta)$ on $\zeta$ is found. Note that implicit in the above procedure is the assumption of a reasonable knowledge of $\theta_0$, which can be estimated from Fig. 2 by comparing $2F(\theta,\zeta)$ with $F(\theta,2\zeta)$ and find the $\theta$ above which these two curves overlap with each other. Below the critical angle $\theta_0$, the main contribution of $F(\theta,\zeta)$ is from small $\theta$s that are dominated by measurements made within the same flux tube, where the relationship in Eq. (8) does not hold.

Figure 3 is our most important result. Several conclusions can be readily drawn from it. First, the fact that the scaling law of Eq. (8) only holds in the solar wind but not in the Earth's magnetotail suggests that current-sheet-like structures, at least those similar to that found in the solar wind, do not exist in the Earth's magnetotail. Since our analysis is done using data from the same instrument onboard Cluster C1 spacecraft for both the solar wind and Earth's magnetotail, this is a very robust conclusion. This finding is consistent with the suggestion of Borovsky (2006) where these current sheets in the solar wind are magnetic walls of flux tubes that have a solar origin. Since in the Earth's magnetotail, there are no such structures, the absence of these current-sheet-like structures is not surprising. However, our results should not be over-interpreted as an affirmative evidence for the Borovsky's proposal. The absence of current-sheet-like structures in the Earth's magnetotail does not mean these structures in the solar wind must have a solar origin.

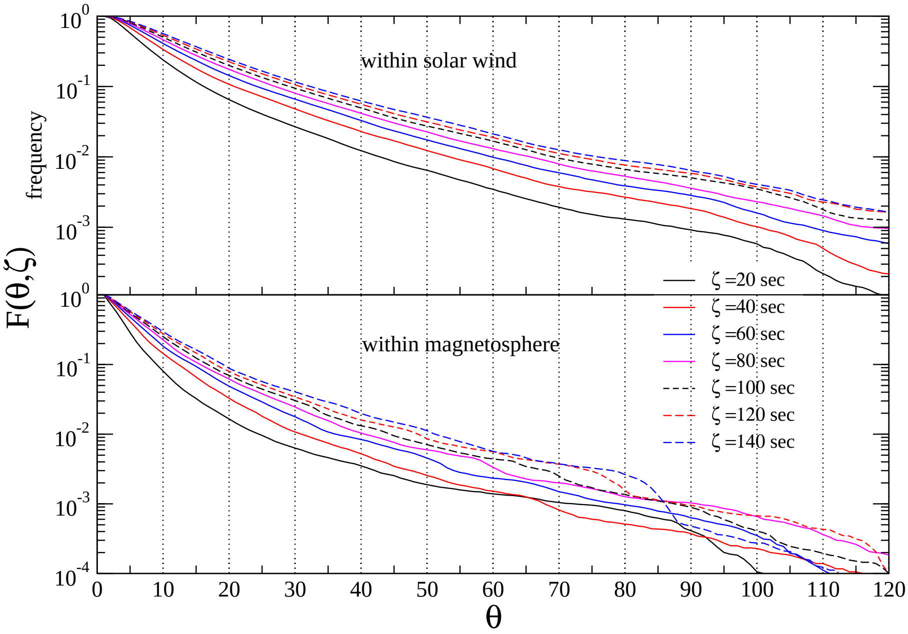

**Fig. 2.** $F(\theta,\zeta)$ as function of $\theta$. The upper panel is during period A, when Cluster C1 is in the solar wind. The lower panel is during period B, when Cluster C1 is inside Earth's magnetotail. Curves for seven $\zeta$ values are shown. See text.

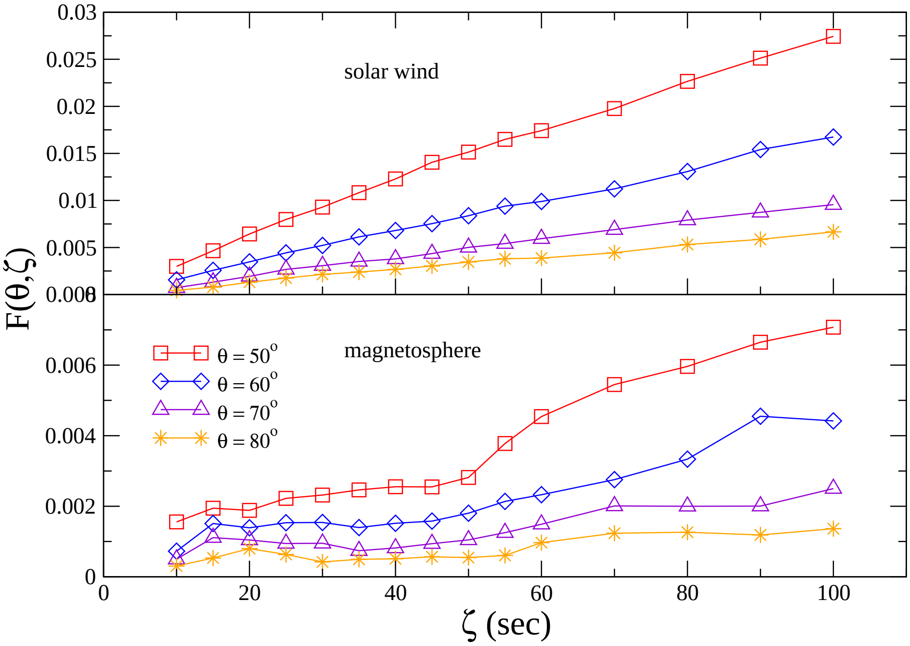

**Fig. 3.** $\zeta$ dependence of $F(\theta,\zeta)$. The upper panel is for period A and the lower panel for period B. X-axis is $\zeta$ and y-axis is $F(\theta,\zeta)$. In both panels, four $\theta$ values are considered. See text for details.

Indeed, these structures in the solar wind may still be the result of non-linear interactions of MHD turbulence and they do not emerge in the Earth's magnetotail could be because the plasma environments of the solar wind and the Earth's magnetotail are vastly different, so that current sheets do not easily develop in the Earth's magnetotail, although other intermittent structures may emerge (Chang, 1999). If this is the case, then it would be very interesting to investigate what are favorable conditions for current sheets to emerge in the solar wind. Secondly, if indeed this scaling law in the solar wind is due to the existence of flux tubes, then one must be cautious in analyzing, for example, the power spectrum and structure functions of the turbulence. This is because the existence of magnetic walls will cause an "artificial" glitch in the magnetic field direction and this glitch will affect the calculation of power spectrum and structure functions since these quantities are ensemble averages of 2-point correlation functions. Clearly, a proper understanding of the intrinsic solar wind MHD turbulence requires a data analysis scheme which can remove the effects of these current sheets. Indeed, in the work of Veltri and Mangeney (1999), a conditioned structure functions technique was introduced in obtaining the scaling properties of solar wind fluctuations by removing the data points representing current sheets from the analysis. A generalization of this technique was reported recently by Salem et al. (2007), who, upon analyzing magnetic field and fluid velocity data from WIND spacecraft, recovered the linear scaling properties of the fluctuations ($\delta B$ and $\delta U$) in the inertial range by removing contributions from various coherent structures, including current sheets.

Assuming measurements with $\theta > 50°$ in Fig. 3 represent flux tube crossings, then Fig. 3 also allows us to estimate the relative probability of the angle changes. By fitting the four curves as straight lines, we obtain the four slopes of $dF/d\zeta$s, from the top to the bottom, $2.69\times10^{-4}$, $1.65\times10^{-4}$, $9.76\times10^{-5}$, $6.65\times10^{-5}$, respectively. Denote $n(\theta_1, \theta_2)$ as the number of measurements with $\theta_1 < \theta < \theta_2$, then we find, to a good approximation, $n(50°, 60°):n(60°, 70°):n(70°, 80°) = 10.9:6.74:3.11$. Thus, the frequency of finding a change of magnetic field direction between two flux tubes in the angles of $(50°, 60°)$ is about 1.5 times that between $(60°, 70°)$, which is in turn about twice that between $(70°, 80°)$.

At smaller angles $\theta < \theta_0$, $F(\theta, \zeta)$s in the solar wind do not obey the $\zeta$ scaling law. Presumably this population of $F(\theta, \zeta)$ at $\theta < \theta_0$ corresponds to measurements where $\hat{b}(t)$ and $\hat{b}(t+\zeta)$ are within the same flux tube. We expect this population to describe local intrinsic turbulence in the solar wind, where each flux tube can be regarded as a sample (instance) of the ensemble of solar wind plasma. The existence of the flux tubes, however, introduces another time (length) scale to the problem and causes a second population of $f(\theta, \zeta)$ to emerge. This second population of $f(\theta, \zeta)$ leads to an "artificial" contribution to the correlation function $R^{\hat{b}}(\zeta)$ as well as the power spectrum and structure functions. It is important for one to remove the effects due to these current sheets in analyzing solar wind MHD turbulence and understanding its intermittent characteristics.

## 4 Conclusions

Using magnetic field data from Cluster C1 spacecraft, we examine in this paper the integrated probability density $F(\theta, \zeta)$ and its $\zeta$ dependence in two plasma environments: the solar wind and the Earth's magnetotail. Our results show that at a given $\theta > \theta_0$, $F(\theta, \zeta)$ increases linearly with $\zeta$ in the solar wind, satisfying the scaling law Eq. (8). On the contrary, there is no such scaling law operating in Earth's magnetotail. This result reveals that while current-sheet-like structures exist in the solar wind, similar structures do not exist inside the Earth's magnetotail. This is consistent with the scenario proposed by Borovsky (2006) where current-sheet-like structures in the solar wind are magnetic walls of relic flux tubes having a solar origin. However, our result does not necessarily prove the correctness of the Borovsky (2006) proposal. One may argue that the fact that this scaling law of $\zeta$ is absent within the Earth's magnetotail because current-sheet-like structures can not easily develop in an environment such as the Earth's magnetotail. If, however, these current sheets in the solar wind are indeed flux tube boundaries that have a solar origin, then our present day analysis of solar wind turbulence needs to be improved because these structures will inevitably introduce a source of MHD turbulence intermittency. A conditioned structure functions technique used in Veltri and Mangeney (1999) and recently in Salem et al. (2007) may help to remove these artificial contributions from these current-sheet-like structures.

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## References

Bartley, W. C., Bukata, R. P., McCrachen, K. G., and Rao, U. R.: Anisotropic cosmic radiation fluxes of solar origin, J. Geophys. Res., 71, 3297–3304, 1966.

Borovsky, J.: The Flux-Tube Texture of the Solar Wind, 2006AGUFMSH43C05B, 2006.

Balogh, A., Carr, C. M., Acuña, M. H., et al.: The Cluster magnetic field investigation: overview of in-flight performance and initial results, Ann. Geophys., 19, 1207–1217, 2001, http://www.ann-geophys.net/19/1207/2001/.

Biskamp, D.: Nonlinear Magnetohydrodynamics, Cambridge University Press, 1993.

Bruno, R., Bavassano, B., Pietropaolo, E., Carbone, V., and Veltri, P.: Effects of intermittency on interplanetary velocity and magnetic fluctuations anisotropy, Geophys. Res. Lett., 26, 3185–3188, 1999.

Bruno, R., Carbone, V., Veltri, P., Pietropaolo, E., and Bavassano, B.: Identifying intermittency events in the solar wind, Plan. Space Sci., 49, 1201–1210, 2001.

Bruno, R., Carbone, V., Sorriso-Valvo, L., and Bavassano, B.: Radial evolution of solar wind intermittency in the inner heliosphere, J. Geophys. Res., 108, SSH 8-1, 1130, 2003.

Bruno, R., Carbone, V., Primavera, L., Malara, F., Sorriso-Valvo, L., Bavassano, B., and Veltri, P.: On the probability distribution function of small-scale interplanetary magnetic field fluctuations, Ann. Geophys., 22, 3751–3769, 2004, http://www.ann-geophys.net/22/3751/2004/.

Bruno, R. and Carbone, V.: The solar wind as a turbulence laboratory, Living Rev. Solar Phys., 2, http://www.livingreviews.org/lrsp-2005-4, 2005.

Burlaga, L. F.: Intermittent turbulence in the solar wind, J. Geophys. Res., 96, 5847–5851, 1991a.

Burlaga, L.: Multifractal structure of the interplanetary magnetic field – Voyager 2 observations near 25 AU, 1987–1988, Geophys. Res. Lett., 18, 69–72, 1991b.

Burlaga, L.: Multifractal structure of speed fluctuations in recurrent streams at 1 AU and near 6 AU Geophys. Res. Lett., 18, 1651–1654, 1991c.

Carbone, V., Bruno, R., and Veltri, P.: Scaling laws in the solar wind turbulence, in: Lecture Notes in Physics, vol. 462: Small-Scale Structures in Three-Dimensional Hydrodynamic and Magnetohydrodynamic Turbulence, proceedings of the workshop held in Nice (France), 10–13 January 1995, edited by: Meneguzzi, M., Pouquet, A., and Sulem, P. L., Springer-Verlag, 153–158, 1995a.

Carbone, V., Veltri, P., and Bruno, R.: Experimental evidence for differences in the extended self-similarity scaling laws between fluid and magnetohydrodynamic turbulent flows, Phys. Rev. Lett., 75, 3110–3113, 1995b.

Chang, T.: Self-organized criticality, multi-fractal spectra, sporadic localized reconnections and intermittent turbulence in the magnetotail, Phys. Plasmas, 6, 4137–4145, 1999.

Chang, T., Tam, S. W. Y., and Wu, C.-C.: Complexity induced anisotropic bimodal intermittent turbulence in space plasmas, Phys. Plasmas, 11, 1287–1299, 2004.

Goldstein, M. L., Klimas, A. J., and Barish, F. D.: Solar Wind Three Proceedings, On the theory of large amplitude Alfvén waves, 385, 1974.

Goldstein, M. L., Roberts, D. A., and Matthaeus, W. H.: Magnetohydrodynamic Turbulence In The Solar Wind, Ann. Rep. Astron. Astrophys., 33, 283–325, 1995.

Horbury, T. S., Balogh, A., Forsyth, R. J., and Smith, E. J.: Magnetic field signatures of unevolved turbulence in solar polar flows, J. Geophys. Res., 101, 405–413, 1996.

Horbury, T. S., Balogh, A., Forsyth, R. J., and Smith, E. J.: Ulysses observations of intermittent heliospheric turbulence, Adv. Space Phys., 19, 847–850, 1997.

Iroshnikov, P. S.: Turbulence of conducting fluids in a strong magnetic field, Sov. Astron., 7, 566–571, 1963.

Kolmogorov, A. N.: The local structure of turbulence in incompressible viscous fluid for very large reynolds numbers, C. R. Acad. Sci. U.S.S.R., 30, 301–305, 1941.

Kraichnan, R. H.: Inertial-range spectrum of hydromagnetic turbulence, Phys. Fluids, 8, 1385–1387, 1965.

Li, G.: Flux tubes in the fast and slow solar wind, Turbulence and nonlinear processes in astrophysical plasmas, AIP, 932, 26–31, 2007.

Li, G.: Identify current-sheet like structures in the solar wind, Astro. Phys. J. Lett., 672, L65–L68, 2008.

Mariani, F., Bavassano, B., Villante, U., and Ness, N. F.: Variations of the occurrence rate of discontinuities in the interplanetary magnetic field, J. Geophys. Res., 78, 8011–8022, 1973.

Marsch, E. and Tu, C.-Y.: On the radial evolution of MHD turbulence in the inner heliosphere, J. Geophys. Res., 95, 8211–8229, 1990.

Marsch, E. and Liu, S.: Structure functions and intermittency of velocity fluctuations in the inner solar wind, Ann. Geophys., 11, 227–238, 1993, http://www.ann-geophys.net/11/227/1993/.

Marsch, E. and Tu, C.-Y.: Non-Gaussian probability distributions of solar wind fluctuations, Ann. Geophys.. 12, 1127–1138, 1994.

Marsch, E. and Tu, C. Y.: Intermittency, non-Gaussian statistics and fractal scaling of MHD fluctuations in the solar wind, Nonlin. Processes Geophys., 4, 101–124, 1997, http://www.nonlin-processes-geophys.net/4/101/1997/.

McCracken, K. G. and Ness, N.: The collimation of cosmic rays by the interplanetary Magentic Field, J. Geophys. Res., 71, 3315–3318, 1966.

Meneveau, C. and Sreenivasan, K. R.: Simple multifractal cascade model for fully developed turbulence, Phys. Rev. Lett., 59, 1424–1427, 1987.

Ruzmaikin, A., Feynman, J., Goldstein, B., and Balogh, A.: Intermittent turbulence in solar wind from the south polar hole, J. Geophys. Res., 100, 3395–3403, 1995.

Salem, C., Mangeney, A., Bale, S. D., Veltri, P., and Bruno, R.: Anomalous scaling and the role of intermittency in solar wind MHD turbulence: new insights, AIP Conference Proceedings, 932, 75–82, 2007.

Tu, C.-Y.: The damping of interplanetary Alfvénic fluctuations and the heating of the solar wind, J. Geophys. Res., 93, 7–20, 1988.

Tu, C.-Y. and Marsch, E.: MHD structures, waves and turbulence in the solar wind: Observations and theories, Space Sci. Res., 73, 1–210, 1995.

Tu, C.-Y. and Marsch, E.: An extended structure-function model and its application to the analysis of solar wind intermittency properties, Ann. Geophys., 14, 270–285, 1996, http://www.ann-geophys.net/14/270/1996/.

Veltri, P. and Mangeney, A.: Scaling Laws and Intermittent Structures in Solar Wind MHD Turbulence, in Solar Wind Nine, AIP Conference Proceedings, 471, 543–546, 1999.

Veltri, P., Nigro, G., Malara, F., Carbone, V., and Mangeney, A.: Intermittency in MHD turbulence and coronal nanoflares modelling, Nonlin. Processes Geophys., 12, 245–255, 2005, http://www.nonlin-processes-geophys.net/12/245/2005/.

Zhou, Ye, Matthaeus, W. H., and Dmitruk, P.: Colloquium: Magnetohydrodynamic turbulence and time scales in astrophysical and space plasmas, Rev. Mod. Phys. 76, 1015–1035, 2004.