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IDENTIFYING CURRENT-SHEET-LIKE STRUCTURES IN THE SOLAR WIND

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ABSTRACT

In past years, measurements of the solar wind plasma have advanced our understanding of MHD turbulence tremendously. At small scales, the solar wind is believed to be very multifractal with nonlinear interactions causing an intermittent energy dissipation, leading to possible current-sheet structures. In this Letter, we propose a systematic data analysis procedure to examine the existence of current sheets in the solar wind. We show that by studying the integrated distribution function $F(\theta, \zeta)$ of the angle between two unit magnetic fields $\hat{\mathbf{b}}(t)$ and $\hat{\mathbf{b}}(t + \zeta)$, as well as its ζ -dependence, one can unambiguously identify the existence of current-sheet-like structures in the solar wind. Using this procedure, we analyze magnetic field data from the VHM/FGM instrument on board the spacecraft *Ulysses* for two periods, one in solar maximum and the other in solar minimum. In both cases, current sheets are clearly inferred. Furthermore, we also outline a procedure that allows the identification of the actual locations of these current sheets. Results from our analysis and the implications of the existence of current sheets in the solar wind are discussed.

Subject headings: MHD — solar wind — Sun: granulation — turbulence

Online material: color figures

1. INTRODUCTION

The solar wind provides us a natural site for studying MHD turbulence. Observations of plasma density ρ , flow speed $\mathbf{U}$, and magnetic field $\mathbf{B}$ by various spacecraft have revealed valuable information about solar wind turbulence and its dynamical evolution (see, e.g., Marsch & Tu [1990] and reviews by Tu & Marsch [1995] and Goldstein et al. [1995]).

In studying solar wind turbulence, the so-called two-point correlation of a certain physical quantity is often used. Consider a physical quantity $\mathcal{P}$, the two-time correlation $R^{\mathcal{P}}(\zeta)$ is defined through $R^{\mathcal{P}}(\zeta) = \langle \mathcal{P}(T)\mathcal{P}(T + \zeta) \rangle$, where ζ is the time lag and the average is an ensemble average. If $\mathcal{P}$ is the magnetic field $\mathbf{B}$ or the plasma velocity $\mathbf{U}$, then $R^{\mathcal{P}}(\zeta)$ is a tensor. One particular choice of $\mathcal{P}$ is $\hat{\mathbf{b}}(t)$, the unit vector of the magnetic field, $\hat{\mathbf{b}}(t) = \mathbf{B}/|\mathbf{B}|$. This leads to

$$R_{ij}^{\hat{\mathbf{b}}}(\zeta) = \langle \hat{\mathbf{b}}_i(t)\hat{\mathbf{b}}_j(t + \zeta) \rangle, \quad (1)$$

where i and j are two Cartesian indices. One can obtain a coordinate-independent quantity from equation (1) by taking the trace of $R^{\hat{\mathbf{b}}}(\zeta)$,

$$\text{tr}[R^{\hat{\mathbf{b}}}(\zeta)] = \langle \hat{\mathbf{b}}(t) \cdot \hat{\mathbf{b}}(t + \zeta) \rangle. \quad (2)$$

Thus, $\text{tr}[R^{\hat{\mathbf{b}}}(\zeta)]$ is simply the ensemble average of the cosine of the angle between $\hat{\mathbf{b}}(t)$ and $\hat{\mathbf{b}}(t + \zeta)$. This average can be also written as

$$\langle \hat{\mathbf{b}}(t) \cdot \hat{\mathbf{b}}(t + \zeta) \rangle = \int f(\theta, \zeta) \cos \theta d\theta, \quad (3)$$

where $f(\theta, \zeta)$, the distribution function of θ , describes the probability density of finding the angle between θ and $\theta + \delta\theta$. If $f(\theta, \zeta)$ is known, $\langle \hat{\mathbf{b}}(t) \cdot \hat{\mathbf{b}}(t + \zeta) \rangle$ can be obtained.

Recently, Borovsky (2006) examined 1 yr of magnetic field data from the *Advanced Composition Explorer* (ACE) spacecraft and obtained the distribution function $g(\theta) = f(\theta, 128 \text{ s})$. Bo-

rovsky (2006) found that $g(\theta)$ can be approximated by two populations as

$$g = \begin{cases} \exp(-\theta/23.2^\circ), & \theta \leq \theta_0, \\ \exp(-\theta/11.3^\circ), & \theta > \theta_0, \end{cases} \quad (4)$$

where θ_0 is a critical angle, above which the second population dominates; Borovsky (2006) suggested that the second population is the result of the ACE spacecraft crossing “magnetic walls” between flux tubes. The idea of plasma in the solar wind being bundled in “spaghetti-like” structures (i.e., flux tubes) is not new. It was first proposed some 40 years ago as an attempt to explain the modulation of cosmic rays (Bartley et al. 1966; McCracken & Ness 1966). Later, Mariani et al. (1973) adopted it to explain the observed variations of the occurrence rate of discontinuities in the interplanetary magnetic field. Recently, Bruno et al. (2001, 2004) and Chang et al. (2004) noted that the existence of flux tubes in the solar wind will introduce another source of solar wind intermittency. Although the concept of flux tubes has been noted by many authors, few attempts have been put forth to verify the existence of these structures. While the work of Borovsky (2006) is stimulating, however, it does not offer unambiguous evidence of the existence of the flux tubes, nor does it allow one to identify the boundaries between these flux tubes.

We note that the second population does not necessarily lead to the existence of flux tubes in the solar wind. As long as there exist structures like magnetic walls and the magnetic field direction of the plasma varies by a significant amount from one side of the wall to the other, then the second population will emerge. Thus, current sheets that are generated by nonlinear interactions in the solar MHD turbulence can serve equally well as the role of magnetic walls that separate plasmas into different tubes, only here the plasmas are not separated into individual bundles.¹ Clearly, the key point here is whether

¹ Numerical simulations (e.g., Zhou et al. 2004) showed that a lot of current sheets can emerge in the solar wind MHD turbulence.

FIG. 1.—Integrated distribution function $F(\theta, \zeta)$ for two example time periods. The left panels show the θ -dependence of $F(\theta, \zeta)$, and the right panels show the ζ -dependence of $F(\theta, \zeta)$. At large angles, $F(\theta, \zeta)$ increases linearly with ζ (dashed lines in the right panels), a consequence of the scaling law (eq. [7]). See text for details. [See the electronic edition of the Journal for a color version of this figure.]

such magnetic-wall-like or current-sheet-like structures exist in the solar wind.

2. CURRENT SHEETS IN THE SOLAR WIND FROM ULYSSES MEASUREMENTS

In the following, we present a data analysis procedure that not only verifies the existence of current sheets in the solar wind but can also pinpoint the exact locations of individual current sheets.

Consider $f(\theta, \zeta)$, which is computed from observational data through

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

Here $N^\zeta(\theta < \theta' < \theta + \Delta\theta)$ is the number of measurements where the angle between $\hat{\mathbf{b}}(t)$ and $\hat{\mathbf{b}}(t + \zeta)$ is within the range of $(\theta, \theta + \Delta\theta)$; $N^\zeta(0 < \theta' < \pi)$ is the total number of measurements. In our analysis, we use $\Delta\theta = 1^\circ$. Note the interval ζ is not to be confused with the measurement resolution δ . In our analysis, the measurement resolution δ of the Vector Helium Magnetometer/Flux Gate Magnetometer (VHM/FGM) on board *Ulysses* is ~ 1 s while the interval ζ ranges from 20 to 160 s. Using δ , we have

$$N^\zeta(0 \leq \theta \leq \pi) = (T - \zeta)/\delta \approx T/\delta, \quad (6)$$

where T is the total period during which the analysis is performed. We assume $T \gg \zeta$ (T is usually days and $\zeta \sim$ minutes). The fact that $N^\zeta(0 \leq \theta \leq \pi)$ is independent of ζ is crucial for our analysis.

TABLE 1
PERIOD SELECTED FOR OUR STUDY^a

Parameter	Solar Minimum	Solar Maximum
Period	1998.43–1998.69	2001.128–2001.154
R (AU)	5.4	1.4
Altitude	$2.7^\circ < \lambda < 4.2^\circ$	$-6^\circ < \lambda < 6^\circ$

^a The trajectory of *Ulysses* is obtained from <http://cohoweb.gsfc.nasa.gov/helios/heli.html>.

This independence can be better seen from the following example. Assuming measurements of the magnetic field are taken at a series of time (1, 2, ..., 1000 s), then if $\zeta = 16$ s, we calculate the angles between magnetic fields of the following time pairs: (1, 17 s), (2, 18 s), ..., (983, 1000 s); and if $\zeta = 32$ s, the following time pairs: (1, 33 s), (2, 34 s), ..., (968, 100 s). Clearly, the number of pairs in both cases is almost the same, although ζ doubles.

We next define the integrated distribution function $F(\theta, \zeta)$ through

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

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

Consider now how $F(\theta, \zeta)$ changes as a function of ζ . Suppose ζ doubles from Δ to 2Δ ($\Delta \gg \delta$). As explained earlier, the total number of pairs ($t, t + \zeta$) does not change. However, the total number of pairs where the two measurements of magnetic field are on opposite sides of the magnetic wall will double. To see this, we consider again the previous example and assume there is one current sheet at $t = 500$ s; then, for $\zeta = 16$ s, the following pairs—(484, 500 s), (485, 501 s), ..., (499, 515 s)—cross the current sheet, and the number of such pairs is 16; if $\zeta = 32$ s, the pairs crossing the sheet will be (468, 500 s), (469, 501 s), ..., (499, 531 s), and the number of such pairs is 32.

Since we expect those large angles (i.e., $\theta > \theta_0$) mainly result from crossings of the current sheet, we have roughly $N^{2\zeta}(\theta < \theta' < \pi) \sim 2N^\zeta(\theta < \theta' < \pi)$. This yields $F(\theta, 2\zeta) \sim 2F(\theta, \zeta)$ when $\theta > \theta_0$. If we generalize this argument from 2 to N , we have

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

Equation (8) is essentially a scaling law of $F(\theta, \zeta)$ on ζ . It is the key to examining the existence of current sheets in the solar wind. As long as the distribution function $F(\theta, \zeta)$ above a certain critical angle θ_0 is dominated by current-sheet crossings, we expect the scaling of ζ on $F(\theta, \zeta)$ to hold. Below the critical angle θ_0 , the main contribution of $F(\theta, \zeta)$ is from small θ 's that are dominated by measurements made within the same side of a current sheet, so we do not expect the relationship in equation (7) to hold.

The above discussion outlines a procedure to examine the existence of current sheets in the solar wind. We now apply it to two solar wind periods. We use the high time resolution magnetic field data from the VHM/FGM on board the spacecraft *Ulysses*. VHM/FGM has a high time resolution of magnetic field data of 1 s (for some periods 2 s), making its data set the most suitable for our current investigation (in comparison, *ACE* magnetic field data used by Borovsky [2006] have only a time resolution of 16 s). Furthermore, *Ulysses*'s polar orbit allows it to probe both the fast and the slow solar wind. Its orbit also reaches out to 5 AU, permitting studies of possible r -dependence of the current sheets (Li 2007).

Figure 1 plots $F(\theta, \zeta)$ for two time periods: the first 1998.43–1998.69 (*upper panels*) and the second 2001.128–2001.154 (*lower panels*). The first period is in the rising phase of solar cycle 23, close to solar minimum. The second period is in the solar maximum of solar cycle 23. The distance and altitude of the *Ulysses* spacecraft during these periods are listed in Table 1. The left two panels plot $F(\theta, \zeta)$ as a function of θ at different

FIG. 2.—Case showing that *Ulysses* crosses a magnetic wall. The left panel is from the 1998.43–1998.69 period and the right panel from the 2001.128–2001.154 period. In both cases, the center times of the pattern give the location of the magnetic wall. [See the electronic edition of the *Journal* for a color version of this figure.]

ζ 's. Curves for four ζ -values are shown. The solid curves are for $\zeta = 20$ s, the short-dashed curves for $\zeta = 40$ s, the dot-dashed curves for $\zeta = 80$ s, and the long-dashed curves for $\zeta = 160$ s. From the figure, we find that $F(\theta, \zeta)$'s for the period of 1998.43–1998.69 (near solar minimum) decrease faster as a function of θ than those for the period 2001.128–2001.154 (near solar maximum). This, of course, reflects the fact that the magnetic field direction changes more drastically during solar maximum. Note that when $\theta \geq 40^\circ$, the curves for different ζ 's seem to be ordered relative to each other by a factor of 2; while at smaller angles, for example, $\theta < 30^\circ$, this ordering does not hold. This proportionality for $F(\theta, \zeta)$'s to ζ at large angles is better seen in the right two panels of Figure 1, where $F(\theta, \zeta)$ is plotted as a function of ζ for two θ 's. The solid lines are for $\theta = 10^\circ$, and the dashed lines for $\theta = 40^\circ$ (scaled by a factor of 10 for better viewing). In both periods, $F(\theta, \zeta)$ for eight ζ 's are shown; these correspond to the filled circles and the asterisks. Fitting the dashed curves by a straight line, we obtain the correlation coefficients as 0.99965 for the 1998.43–1998.69 period and 0.9982 for the 2001.128–2001.154 period. For a total of eight data points, this shows unambiguously that $F(\theta, \zeta)$ increases linearly with respect to ζ at large angles. This linear dependence, of course, is just the scaling law as given by equation (7). In contrast to the dashed curves at $\theta = 10^\circ$, the solid curves (i.e., $\theta = 10^\circ$) clearly violate equation (7). This again reflects the fact that smaller angles are largely from measurements within the same side of a current sheet; thus, equation (7) does not hold.

By plotting $F(\theta, \zeta)$, we can verify the scaling law of equation (7). However, $F(\theta, \zeta)$ is a statistical quantity, so Figure 1 does not allow us to identify individual current sheets. In the following, we show how one can identify individual current sheets.

Suppose that the spacecraft crosses a current sheet at time $t = T$; then during the period $T - \zeta < t < T$, $\hat{b}(t)$ and $\hat{b}(t + \zeta)$ will lie on opposite sides of the current sheet. So for the majority of the following measurements— $\hat{b}(T - \zeta) \cdot \hat{b}(T)$, $\hat{b}(T - \zeta + \delta) \cdot \hat{b}(T + \delta)$, ..., $\hat{b}(T - \delta) \cdot \hat{b}(T + \zeta - \delta)$ —we expect the resultant angles to be larger than θ_0 . Of course, by the law of statistics, there will be a small fraction of these θ 's smaller than θ_0 . One can now identify the location of the current sheets by searching

for a series of measurements of θ 's that satisfy the following: (1) the length of the series is about ζ , and (2) most θ 's in the series are larger than θ_0 . When such a time series (hereafter “target series”) is found, the time at the end of the target series will correspond to the location of the current sheet. One can improve this method by considering again measurements of multiple ζ 's. Then because the starting time of the target series is $T - \zeta$ and the ending time is T , the obtained target series from using different ζ 's should exhibit a pattern where the ending times are approximately the same ($\sim T$) and the starting times are ordered by $T - \zeta$. A useful technique for better recognizing the pattern is to include $t + \zeta$ in the target series. This inclusion will cause the target series to be symmetric with respect to $t = T$ and have a length of 2ζ (from $T - \zeta$ to $T + \zeta$). This symmetric pattern allows an easier identification of T than the original asymmetric pattern. Furthermore, it also provides an estimate of the thickness of the current sheet. Suppose a current sheet has a finite thickness d and assume that a jump in θ only occurs when $t < T$ and $t + \zeta > T + d$ (i.e., neither one of the two measurements can reside inside of the current sheet); then the interval of having a θ larger than θ_0 will change to $(T + d - \zeta, T + \zeta)$. The length of the interval now becomes $2\zeta - d$. From the measured length of the target series, one can now estimate the value of d . The procedure, although simple in principle, requires a reasonably well developed “pattern recognition” routine to facilitate automatic identifications of the current sheets (G. Li 2008, in preparation).

Figure 2 shows two example cases where current sheets are identified. The left panel shows a 220 s period taken from the period of 1998.43–1998.69 (Fig. 1, upper panels). The right panel shows a 220 s period taken from the period of 2001.128–2001.154 (Fig. 1, lower panels). Time is along the x-axis. A nonzero y-value at a time t signals that θ at that time is larger than θ_0 (taken to be 40° in both cases). Three ζ 's are considered: the plus signs for $\zeta = 24$ s, the diamonds for $\zeta = 48$ s, and the asterisks for $\zeta = 96$ s. The y-values for the plus signs, diamonds, and asterisks are set to be 1.0, 1.1, and 1.2, respectively, to separate them. From the figure, one can easily identify the center time of the signals at $\sim t = 5,034,872$ s, which is the location of the current sheet. Using the time duration of these signals, one can also estimate the width of the current sheet, which is about ~ 4 – 6 s. The right panel of Figure 2 is for a period taken from the right panel of Figure 1. Here one finds the dot-dashed line is broken. However, the overall pattern from all three lines unambiguously shows that the location of the current sheet is $\sim 11,538,321$ s and the corresponding width of the current sheet is ~ 10 – 12 s. In contrast to the pattern shown in Figure 2, Figure 3 shows two cases where nonzero y-values ($\theta > \theta_0$) simply appear as the result of the law of statistics. Here we find the nonzero y's appear sporadic and irregular. Clearly, using the collective pattern by multiple ζ 's can effectively exclude these “false” signals of current-sheet crossings. Using a pattern recognition routine, one can also identify the frequency of magnetic wall crossings (G. Li 2008, in preparation).

3. DISCUSSION AND CONCLUSION

In studying the fluctuations of the solar wind, it has been noted that the magnetic field strength tends to be constant while the direction fluctuates with respect to the average background field direction (Goldstein et al. 1974). Barnes (1981) interpreted this phenomenon as the magnetic field vector $\mathbf{B}$ undergoing a

FIG. 3.—Similar to Fig. 2, but with a “false” pattern that does not yield a magnetic wall crossing. [See the electronic edition of the *Journal* for a color version of this figure.]

“random walk” process on a sphere (a constant $|\mathbf{B}|$). In this picture, the fluctuation of the solar wind magnetic field is better described by a tangled and turbulent field than planar (Alfvénic) waves. It is conceivable that the first population of $f(\theta, \zeta)$ obtained in this analysis is a consequence of this random motion of the magnetic field vector on a sphere. The second population of $f(\theta, \zeta)$, showing an abrupt change of the magnetic field direction, however, suggests that there are current-sheet-like structures in the solar wind. This drastic change of magnetic field direction implies that the solar wind is intermittent. Indeed, in a recent study of solar wind MHD turbulence, using a Haar wavelets technique, Veltri & Mangeney (1999; also see Veltri et al. 2005) analyzed velocity and magnetic field data from the *ISEE* space experiment and calculated power spectra and structure functions for a time range between 1 minute and about 1 day and found that the most intermittent structures in solar wind turbulence are one-dimensional current sheets where the magnetic field rotates by an angle of about 120° – 130° . Although the detailed formation process of these current sheets is still not

fully understood, it is closely related to nonlinear dynamics in the solar wind MHD turbulence.

Different from that employed by Veltri & Mangeney (1999), our analysis also shows that there are current-sheet-like structures in the solar wind. In our analysis, the change of magnetic field directions from one side of the current sheet to the other side is found to be $\theta \sim 50^\circ$, somewhat smaller than that found in Veltri & Mangeney (1999). If solar wind plasma indeed resides in flux tubes (Borovsky 2006), then it is possible that the current sheets we identify are the magnetic walls separating those flux tubes. In this case, the first population of $f(\theta, \zeta)$ corresponds to the measurements where $\hat{\mathbf{b}}(t)$ and $\hat{\mathbf{b}}(t + \zeta)$ are within the same flux tube, and the second population of $f(\theta, \zeta)$ corresponds to the measurements where $\hat{\mathbf{b}}(t)$ and $\hat{\mathbf{b}}(t + \zeta)$ are in different flux tubes. Clearly, the existence of the flux tubes introduces a length (time) scale and causes the second population of $f(\theta, \zeta)$ to emerge. It also affects the power spectrum of the turbulence since the power spectrum is just a Fourier transform of a two-point correlation function.

To summarize, we have outlined in this Letter a procedure to identify current-sheet-like structures in the solar wind. We show that by studying the integrated distribution function $F(\theta, \zeta)$ of the angle between $\hat{\mathbf{b}}(t)$ and $\hat{\mathbf{b}}(t + \zeta)$ and its ζ -dependence, one can infer the existence of current sheets in the solar wind. We also show how one can locate the exact locations of these current sheets through a pattern recognition technique. Using magnetic field data from *Ulysses*, we applied our analysis to two example periods. The results are shown in Figures 1, 2, and 3. The procedure outlined here will be valuable in studying structures and turbulence properties in the solar wind.

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