Effect of Current Sheets on the Solar Wind Magnetic Field Power Spectrum from the Ulysses Observation: From Kraichnan to Kolmogorov Scaling

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The MHD turbulence theory developed by Iroshnikov and Kraichnan predicts a $k^{-1.5}$ power spectrum. Solar wind observations, however, often show a $k^{-5/3}$ Kolmogorov scaling. Based on 3 years worth of Ulysses magnetic field data where over 28,000 current sheets are identified, we propose that the current sheet is the cause of the Kolmogorov scaling. We show that for 5 longest current-sheet-free periods the magnetic field power spectra are all described by the Iroshnikov-Kraichnan scaling. In comparison, for 5 periods that have the most number of current sheets, the power spectra all exhibit Kolmogorov scaling. The implication of our results is discussed.

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Magnetohydrodynamics (MHD) turbulence has been a central topic of space plasma physics [1–3]. This is partly because, comparing to often short-lived terrestrial experiments, solar wind provides, over a long period of time, a natural laboratory for studying collisionless plasma.

The first hydrodynamic turbulence theory was proposed by Kolmogorov [4] (hereafter the K41 theory). From dimensional analysis, Kolmogorov [4] showed that the turbulence power spectrum is a power law in the inertial range where the energy dissipation rate $\varepsilon$ is scale-independent. Indeed, at scale $l$, the dissipation rate is given by $\varepsilon(l) \sim v_A^3/l$, which yields a turbulence power $I_{\text{hydro}}(k) \sim k^{-5/3}$. In the case of (incompressible) MHD turbulence, the energy cascading is mediated by Alfvén wave packets. This introduces the Alfvén speed $V_A$ into the picture, and the energy dissipation rate becomes $\varepsilon(l) \sim v_A^3/(V_A l)$ (assuming equal numbers of counterpropagating Alfvén waves). As a consequence, the turbulence power becomes $I_{\text{MHD}}(k) \sim k^{-3/2}$ [5,6] [hereafter the Iroshnikov-Kraichnan (IK) theory].

The observed fluctuations of $\delta B$ and $\delta v$ in the solar wind, however, are often K41-like and have power-law exponents of $\sim -5/3$ [7–10]. This is perhaps due to several reasons. First, in the solar wind there are more Alfvén waves propagating outwards than inwards. This situation contradicts the assumption made in Refs. [5,6]; therefore, an IK scaling is not evident. Furthermore, the Alfvén waves may be oblique, and the dissipation process can be anisotropic [11–13] such that the cascading occurs mainly along $k_\perp$. As argued in Ref. [12], when the Alfvén waves are highly perpendicular, the decorrelation time due to Alfvén wave cascading $\tau_A$ will become larger than the decorrelation time due to nonlinear effect $\tau_{\text{NL}}$, so the cascading is dominated by nonlinear effects where a scaling of K41 will emerge.

While there are theoretical grounds to advocate both the IK scaling and the K41 scaling for the solar wind MHD turbulence, recent analyses based on a conditional wavelet analysis of the structure function [14–16] have shown that the magnetic field and velocity components of the solar wind can exhibit K41 and IK scaling at the same time. By studying the structure functions of the solar wind $\delta B$ and $\delta v$, Chapman and Hnat [17] showed that the fluctuations in velocity are a linear superposition of two types, the first being compressive and hydrodynamiclike and obeying the K41 scaling and the second being Alfvénic and obeying the IK scaling. Recently, using WIND Magnetic Field Investigation data, Podesta and Borovsky [18] found that the spectral slope for the total energy (kinetic and magnetic) is correlated with the normalized helicity $\sigma_c$ such that when $\sigma_c \sim 1$ an IK scaling is found and when $\sigma_c \sim 0$ a K41 scaling is found.

In this work, we take a different approach from all above studies in an attempt to understanding the cause of and the difference between the K41 scaling and the IK scaling of the solar wind MHD turbulence. Instead of assuming the
MHD turbulence to be anisotropic and decompose the power spectrum into the parallel and perpendicular directions, we examine the total power spectra for the magnetic field in selected intervals. In particular, we compare the power spectra in intervals (i) that are current-sheet-free and (ii) that are current-sheet-abundant. Extending our earlier work [19], we propose that the current sheet (or the absence of it) in the solar wind is the cause of the K41 (or the IK) scaling of the solar wind MHD turbulence power spectra.

A current sheet is a 2D structure where the magnetic field direction changes significantly from one side to the other. The current sheet is a major source of solar wind MHD turbulence intermittency. Using a Haar wavelets technique and magnetic field and fluid velocity data from the International Sun-Earth Explorer space experiment, Veltri and Mangeney [14] calculated the solar wind power spectra and structure functions for a time range between 1 min to about 1 day. They found that the most intermittent structures in the solar wind are current sheets where the magnetic field rotates by an angle of about 120°–130°. In another study, Bruno et al. [20] performed a minimum variance analysis of the solar wind magnetic field data by using Helios 2 data at 0.9 AU and showed that the magnetic field direction at times undergo abrupt changes, implying the presence of a current sheet.

While the presence of current sheets in the solar wind is clear, the origin of them is still a puzzle. On one hand, numerical MHD simulations [21,22] suggest that current sheets emerge as the dynamical evolution of the nonlinear interactions of the solar wind MHD turbulence. On the other hand, Bruno et al. [20] and later Borovsky [23] have suggested that these current sheets could be “magnetic walls” of randomly oriented flux tubes in the solar wind which can be traced back to the surface of the Sun. In this picture, the plasma in the solar wind is bundled in “spaghetti-like” flux tubes. Such a spaghetti-like picture of the solar wind has been suggested by Bartley et al. [24] and McCracken and Ness [25] as an attempt to explain the modulation of cosmic rays and was later adopted by Mariani et al. [26] to explain the observed variations in the occurrence rate of discontinuities in the interplanetary magnetic field. Recently, Qin and Li [27] showed that the existence of current sheets can affect the transport of solar energetic particles and cosmic rays.

To identify current sheets in the solar wind, Li [28,29], extending Ref. [30], developed a method which is based on the $\zeta$-scaling properties of the angle $\theta = \cos^{-1}[\hat{B}(t) \cdot \hat{B}(t + \zeta)]$. Applying this method to magnetic field data from Cluster spacecraft for two selected periods, Li et al. [31] found that, unlike in the solar wind, there was no clear signature of current sheets in the Earth’s magnetosphere. The study of Li et al. [31] therefore is consistent with the “flux tube” picture of the solar wind as proposed in Refs. [20,23]. Based on the previous work of Li [28,29], Miao, Peng, and Li [32] developed an automatic data analysis routine of current-sheet identification. Using this routine, Miao, Peng, and Li [32] analyzed more than 3 years of magnetic field data from the Ulysses spacecraft magnetic field experiment and identified more than 28 000 current sheets. They found that current sheets are common in the solar wind. The average waiting time between adjacent current sheets is about half an hour to a couple of hours [32]. With such a frequency, these current sheets will affect the power spectrum analysis of the solar wind MHD turbulence. The first attempt to understand the effects of a current sheet on the solar wind MHD turbulence power spectrum was reported by Qin, Hu, and Li [19]. Using a cell model of the solar wind, Li et al. [33] reported that an initially IK-scaling power spectrum without current sheets can evolve to a K41 scaling when current sheets are added to the system. Using more than eight years of data from Advanced Composition Explorer observation, Borovsky [34] studied the effect of the strong discontinuities to the power spectrum of the solar wind. By constructing an artificial time series that preserves the timing and amplitudes of the discontinuities, Borovsky [34] showed that the strong discontinuities can produce a power-law spectrum in the inertial subrange with a K41-type scaling.

The study of Borovsky [34] involves data massage through the construction of artificial time-series data. In this work, we examine the solar wind MHD power spectrum by using real time solar wind data from Ulysses spacecraft observation. We first use the current sheets identified in Ref. [32] to obtain all periods between adjacent current sheets. These periods, by construction, are current-sheet-free. From these periods we identify those that are longer than 1 day (corresponding to a frequency of $10^{-4}$ Hz) and perform power spectrum analysis in these periods. We then select, as a control group, periods that are current-sheet-abundant and perform power spectrum analysis in these periods. By juxtaposing these, the effects of current sheets on the power spectrum can be clearly seen. For a current-sheet-free period, we expect that the spacecraft resides within a single flux tube and the period under investigation is free of nonlinear interaction. Therefore, the dissipation is dominated by Alfvén wave cascading and a power spectrum of IK scaling emerges. On the other hand, a current-sheet-abundant period may contain multiple crossings of flux tubes. Furthermore, because the spatial scale of these flux tubes is quite large and its corresponding wave number is in the containing range (the $1/k$ portion) of the spectrum [35], so nonlinear interaction should also be present which can generate highly perpendicular Alfvén waves and lead to a Kolmogorov scaling [12].

We use magnetic field measurements from the Ulysses vector helium and flux gate magnetometer [36] instrument. The period of our study is from day 300 in 1996 to day 365 in 1997, and the other from day 1 in 2004 to day 3 in 2006 [32]. We exclude periods that contain shocks.

From these 3 years worth of data, we obtain a total of 5 current-sheet-free periods that (i) have no significant data
We also use the common fluctuations and examining their properties [9,10,40–43].

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identical in all five fitting frequency ranges, suggesting

are very similar. The fitted spectral indices are nearly

are latitude and longitude of the Ulysses spacecraft, respectively.

The uncertainty of $\gamma$ is from a $\chi^2$ fitting of the Welsh spectrum assuming a good fit [37].

The difference between the power-law exponent (\(\gamma\)'s) in the left and the right columns is significant. It appears that the presence of a current sheet changes the power-law spectrum of the solar wind magnetic field from the IK scaling to the K41 scaling. Because current sheets are common, we therefore expect to often find a

gap, (ii) have durations longer than 24 hours (except one
event whose duration is 23.5 hours), and (iii) have no clear
signatures of transient structures such as shocks. We list
these periods in Table I. In the table, the first column shows
the start times of the interval, which are marked in the
format of (yyyy-mm-dd/hh:mm). The second column shows
the duration of the intervals in days. The third column is the number of current sheets identified within
the selected intervals. For current-sheet-free periods, these
are zero. The fourth column is the fitted exponent of the
power index $\gamma$ with uncertainties. The frequency range for
the fittings is (10^{-3}, 10^{-1}) Hz except for the 2004-03-02
case, where (10^{-3}, 5 \times 10^{-1}) Hz is used. From the fifth to
the eighth columns, the solar wind speed, the heliocentric
distance, and the latitude $\phi$ and longitude $\theta$ of the Ulysses
spacecraft are shown. Also shown in Table I are five 1-day
periods that are current-sheet-abundant.

Figure 1 plots the spectra we obtained for these periods.
The left panel corresponds to the periods that are current-
sheet-free. The right panel corresponds to the periods that
are current-sheet-abundant. The power spectra are ob-
tained by using the direct autocorrelation matrix method
of Blackman and Tukey [38] with a prewhitening and
postdarkening process [9]. We also use the common
Welch method by averaging periodograms (e.g., [39])
that uses the technique of involving segmentation of
time-series data. The spectra obtained from both methods
are very similar. The fitted spectral indices are nearly
identical in all five fitting frequency ranges, suggesting
our result is robust. At very low frequencies, the direct
method of Blackman and Tukey [38], without segmenta-
tion, yields a spectrum having a higher magnitude than the
Welch method. The direct method is now commonly used in
calculating the power spectral densities of interplanetary
fluctuations and examining their properties [9,10,40–43].

To guide the eyes, both a $k^{-1.5}$ (the lower straight line, in
blue) and a $k^{-5/3}$ (the upper straight line, in red) curve are
shown in all subfigures. What is clear from the figure is that
the power spectra in current-sheet-free periods (the left
panel) are more IK-like ($f^{-1.5}$) and the power spectra in
current-sheet-abundant periods (the right panel) are more
K41-like ($f^{-1.7}$). The difference between the power-law
exponent ($\gamma$'s) in the left and the right columns is signifi-
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![FIG. 1 (color online). Power spectra for current-sheet-free periods (left) and current-sheet-abundant periods (right).](125001-3)
The $k^{-5/3}$ spectrum from the solar wind observation. This is in agreement with Refs. [19,34]. Also note the bendovers at low frequencies (between $10^{-4}$ and $10^{-3}$ Hz) in the right panel and the absence of them in the left panel. This seems to suggest that the presence of a current sheet will lead to the development of the “energy containing” range at lower frequency.

Figure 1 is our most important finding. It shows that the presence of current sheets can strongly affect the power analysis of the solar wind magnetic field. Depending on whether or not current sheets are present, either K41 scaling or an IK scaling may arise. Our findings are important because they imply that a proper analysis of the solar wind power spectrum must take into account the effects of current sheets and possibly other intermittent structures.

In summary, in this Letter, we examined the effects of current sheets on the power spectrum of the solar wind magnetic field. We identify periods that are current-sheet-free and that are current-sheet-abundant. We find that the power spectra for current-sheet-abundant periods are K41-like, and the power spectra for current-sheet-free periods are IK-like. Based on this finding, we suggest that the current sheet or the absence of it is the cause of a K41 scaling or an IK scaling of the solar wind magnetic field power spectrum. The fact that solar wind MHD observations often find a K41 scaling is because the current sheets frequently occur in the solar wind.

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