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

G. Li, B. Miao, Q. Hu, and G. Qin

Phys. Rev. Lett. **106**, 125001 — Published 21 March 2011
DOI: 10.1103/PhysRevLett.106.125001

Effect of current sheets on the solar wind magnetic field power spectrum from the Ulysses observation — from Kraichnan to Kolmogorov scaling

G. Li*

Dept. of Physics and CSPAR, Univ. of Alabama in Huntsville, AL 35899

B. Miao

CAS Key Laboratory of Basic Plasma Physics,

School of Earth and Space Sciences,

University of Science and Technology of China, Hefei, Anhui 230026

Q. Hu

CSPAR, Univ. of Alabama in Huntsville, AL 35899

G. Qin

State Key Laboratory of SpaceWeather,

Center for Space Science and Applied Research,

Chinese Academy of Sciences, Beijing 100190

Abstract

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 a 3-year worth Ulysses magnetic field data where over 28000 current sheets are identified, we propose that 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 IK-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.

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 is proposed by Kolmogorov [4] (hereafter 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 ϵ is scale independent. Indeed, at scale l, the dissipation rate is given by $\epsilon(l) \sim v_l^3/l$, which yields a turbulence power $I_{hydro}(k) \sim k^{-5/3}$. 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 $\epsilon(l) \sim v_l^4/(V_A l)$ (assuming equal numbers of counter propagating Alfvén waves). As a consequence, the turbulence power becomes $I_{MHD}(k) \sim k^{-3/2}$ [5, 6] (hereafter IK theory).

The observed fluctuations of δB and δv 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. Firstly, in the solar wind there are more Alfvén waves propagating outwards than inwards. This situation contradicts with the assumption made in [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 [12], when the Alfvén waves are highly perpendicular, the decorrelation time due to Alfvén wave cascading τ_A will become larger than the decorrelation time due to non-linear effect τ_{NL} so the cascading is dominated by non-linear 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 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 δv and δB, Chapman and Hnat [17] showed that the fluctuations in velocity is a linear superposition of two types. The first being compressive and hydrodynamic-like and obeys the K41 scaling and the second being Alfvénic and obeys the IK scaling. They further argued that the turbulent solar wind may be comprised of two weakly interacting components: one from the process that generates the solar wind at the corona, having an IK scaling, and the other intrinsically evolves in the high Reynolds number solar wind, having a K41 scaling. Recently, using WIND MFI data, Podesta and Borovsky [18] found that the spectral slope for the total energy (kinetic and magnetic) is correlated with the normalized helicity σ_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 1) that are current sheet free and 2) that are current sheet abundant. Extending our earlier work [19], we propose that 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. 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 ISEE space experiment, Veltri and Mangeney [14] calculated the solar wind power spectra and structure functions for a time range between 1 minute to about 1 day. They found that the most intermittent structures in the solar wind are current sheets where magnetic field rotates by an angle of about 120-130 degrees. In another study, Bruno *et al.* [20] performed a minimum variance analysis of the solar wind magnetic field data using Helios 2 data at 0.9 AU and showed that the magnetic field direction at times undergo abrupt changes, implying the presence of current sheet.

While the presence of current sheet 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 are 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 interplanetary magnetic field. Recently Qin and Li [27] showed that the existence of current sheets can affect the transport of solar energetic cosmic rays.

To identify current sheets in the solar wind, Li [28, 29], extending [30], developed a method which is based on the ζ-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 [20] and [23]. Based on the previous work of Li [28, 29], Miao *et al.* [32] developed an automatic data analysis routine of current sheet identification. Using this routine, Miao *et al.* [32] analyzed more than 3 years magnetic field data from Ulysses spacecraft magnetic field experiment and identified more than 28000 current sheets. Miao *et al.* [32] 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, they will affect the power spectrum analysis of the solar wind MHD turbulence. The first attempt to understand the effects of current sheet on the solar wind MHD turbulence power spectrum was reported by Qin *et al.* [19]. Using a cell model of the solar wind, Qin *et al.* [19], 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-year’s data from ACE 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 sub-range with a K41-type scaling.

The study of Borovsky [34] involves data massage through the construction of an artificial time series data. In this work we examine the solar wind MHD power spectrum using real time solar wind data from Ulysses spacecraft observation. We first use the current sheets identified in [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 reside within a single flux tube and the period under investigation is free of non-linear 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 supergranulation is quite large and its corresponding wavenumber is in the containing range (the $1/k$ portion) of the spectrum [35], so non-linear 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 VHM/FGM [36] instrument. The period of our study is from day 300 in 1996 to day 365 in 1997, and the other from the day 1 in 2004 to day 3 in 2006 [32]. To minimize the influence of, e.g., transient structures such as CMEs, we study only the solar minimum periods. We also exclude periods that contain shocks.

From these 3-year worth of data, we obtain a total of 5 current-sheet free periods that 1) have no significant data gap, 2) have durations longer than 24 hours (except one event whose duration is 23.5 hours), and 3) that 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 time 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 γ. The frequency range for the fittings is $(10^{-3}, 10^{-1})$ Hz except for the 2004-03-02 case, where $(10^{-3}, 5 * 10^{-1})$ Hz is used. From the 5-th to the 8-th columns, the solar wind speed, the heliocentric distance and the latitude ϕ and longitude θ 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 obtained by using the direct auto-correlation matrix method of Blackman and Tukey [37] with a pre-whitening and post-darkening process [9]. We also use the common Welch method by averaging periodograms (e.g., [38]) 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 [37], without segmentation, 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, 39–42] ,

To guide the eyes, both a $k^{-1.5}$ (blue) and a $k^{-5/3}$ (red) curves 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 (γ's) in the left and the right columns is significant. Using the spectra from the Welsh method, both γ and its uncertainty from a χ^2 fitting, assuming a good fit [43], are included in Table I. Note, the values of γ's depend on the choice of the frequency range, so the seemingly small uncertainties of γ should not be over-interpreted. It appears that the presence of current sheet lifts up 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 $k^{-5/3}$ spectrum from the solar wind observation. This is in agreement with [19, 34]. Also note the bend-overs 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 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 solar wind magnetic field. Depending on whether or not current sheets are present in the periods of study, either K41-scaling or IK-scaling may arise. Therefore it is important to characterize the selected periods in terms of the number of current sheets for future solar wind power analysis.

Current sheet is perhaps the most common intermittent structure in the solar wind. They

TABLE I. Selected current-sheet free and current-sheet abundant periods. [a]

Case	duration	N	γ [b]	V_{SW}	R	ϕ	θ
1997-12-22/21:18	1.639	0	-1.55 ± 0.026	348	5.140	-21.54	307.73
2004-03-02/09:37	1.567	0	-1.58 ± 0.024	548	5.086	-23.08	281.06
2004-10-21/04:20	1.256	0	-1.52 ± 0.014	558	5.362	-0.41	355.21
2004-01-25/22:25	1.053	0	-1.44 ± 0.017	374	5.175	-20.45	327.16
1997-09-11/02:31	0.98	0	-1.51 ± 0.024	464	4.735	18.61	44.95
2005-09-29/00:00:00	1.000	111	-1.72 ± 0.016	746	4.768	-30.82	156.91
2005-11-21/00:00:00	1.000	108	-1.81 ± 0.026	577	4.606	-34.27	104.99
2005-03-16/00:00:00	1.000	90	-1.92 ± 0.019	425	5.204	-19.49	344.90
2005-09-28/00:00:00	1.000	87	-1.71 ± 0.017	714	4.771	-30.75	157.88
1996-11-04/00:00:00	1.000	86	-1.68 ± 0.016	695	4.521	22.99	110.59

[a] Duration is in days, V_{SW} is in km/s, R is in AU, N is the number of current sheet, ϕ and θ are Latitude and Longitude of the Ulysses spacecraft respectively.

[b] The uncertainty of γ is from a χ^2 fitting of the Welsh spectrum assuming a good fit [43].

may emerge from nonlinear interactions [21] or are relic "magnetic walls" originate from the surface of the Sun [20, 30]. 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 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.

Our findings are important because they imply that a proper analyses of solar wind power spectrum must take into account the effects of current sheets and possibly other intermittent structures.

This work is supported in part by a NSF Early CAREER grant ATM-0847719, a NASA NNX07AL52A (EpSCoR) grant and an ORAU Ralph E Power Junior Faculty Enhancement Award.

* gang.li@uah.edu

[1] C. Tu and E. Marsch, Space Sci. Rev. **73**, 1 (1995).

[2] M. L. Goldstein, D. A. Roberts, and W. H. Matthaeus, Ann. Rev. Astron. Astrophys. **33**, 283 (1995).

[3] R. Bruno and V. Carbone, Living Reviews in Solar Physics **2** (2005).

[4] A. Kolmogorov, C. R. Acad. Sci. URSS **30**, 301 (1941).

[5] P. S. Iroshnikov, Soviet Astronomy **7**, 566 (1964).

[6] Kraichnan, Phys. Fluids **8**, 1385 (1965).

[7] M. I. Goldstein, Astrophysics and Space Science **277**, 349 (2001).

[8] T. S. Horbury, M. A. Forman, and S. Oughton, Plasma Phys. Control. Fusion **47**, B703 (2005).

[9] R. Leamon, C. Smith, N. Ness, W. H. Matthaeus, and H. Wong, Journal Of Geophysical Research-space Physics **103**, 4775 (1998).

[10] C. W. Smith, B. J. Vasquez, and K. Hamilton, J. Geophys. Res. **111, doi:10.1029/2006JA011651**, A09111 (2006).

[11] J. V. Shebalin, W. H. Matthaeus, and D. Montgomery, J. Plasma Phys. **29**, 525 (1983).

[12] S. Oughton and W. H. Matthaeus, Nonlinear Proc. Geophys. **12**, 299 (2005).

[13] B. D. Chandran, Astrophysical Journal **685**, 646 (2008).

[14] P. Veltri and A. Mangeney, in *American Institute of Physics Conference Series*, American Institute of Physics Conference Series, Vol. 471, edited by S. R. Habbal, R. Esser, J. V. Hollweg, and P. A. Isenberg (1999) pp. 543–546.

[15] C. Salem, A. Mangeney, S. D. Bale, P. Veltri, and R. Bruno, AIP Conference Proceedings **932**, 75 (2007).

[16] C. Salem, A. Mangeney, S. D. Bale, and P. Veltri, Astrophys. J. **702**, 537 (2009).

[17] S. C. Chapman and B. Hnat, Geophys. Res. Lett. **34**, L17103 (2007).

[18] J. J. Podesta and J. E. Borovsky, Physics of Plasmas **17**, 112905 (2010).

[19] G. Qin, Q. Hu, and G. Li, in *AGU Fall, NG21A-03* (2009).

[20] R. Bruno, V. Carbone, P. Veltri, E. Pietropaolo, and B. Bavassano, Planet Space Sci. **49**, 1201 (2001).

[21] Y. Zhou, W. Matthaeus, and P. Dmitruk, Rev. Mod. Phys. **76**, 1015 (2004).

[22] T. Chang, S. Tam, and C. Wu, Phys. Plasmas **11**, 1287 (2004).

[23] J. E. Borovsky, J. Geophys. Res-Space Phys. **113** (2008), 10.1029/2007JA012684.

[24] W. C. Bartley, R. P. Bukata, K. G. McCracken, and U. R. Rao, J. Geophys. Res. **71**, 3297 (1966).

[25] K. McCracken and N. Ness, J. Geophys. Res. **71**, 3315 (1966).

[26] F. Mariani, Bavassan.B, U. Villante, and N. Ness, J. Geophys. Res. **78**, 8011 (1973).

[27] G. Qin and G. Li, Astrophys. J. **682**, L129 (2008).

[28] G. Li, AIP Conference Proceedings **932**, 26 (2007).

[29] G. Li, Astrophys. J. Lett. **672**, L65 (2008).

[30] J. E. Borovsky, in *Fall AGU Meeting,* (2006).

[31] G. Li, E. Lee, and G. Parks, Ann. Geophys. **26**, 1889 (2008).

[32] B. Miao, B. Peng, and G. Li, submitted to Ann. Geophysicae (2010).

[33] G. Li, G. Qin, Q. Hu, and B. Miao, to be submitted to Astrophys. J. (2010).

[34] J. E. Borovsky, Phys. Rev. Lett. **105**, 111102 (2010).

[35] A. Ruzmaikin, B. E. Goldstein, E. J. Smith, and A. Balogh, Proceedings of the eigth international solar wind conference **382**, 225 (1996).

[36] A. Balogh, T. J. Beek, R. J. Forsyth, P. C. Hedgecock, R. J. Marquedant, E. J. Smith, D. J. Southwood, and B. T. Tsurutani, Astron. Astrophys. Suppl. **92**, 221 (1992).

[37] R. Blackman and J. W. Tukey, *The measurement of power spectra* (1958).

[38] B. Porat, *A course in digital signal processing* (John Wiley & Sons, New York, 1997).

[39] B. T. MacBride, C. W. Smith, and B. J. Vasquez, J. Geophys. Res. **115**, A07105 (2010).

[40] J. A. Tessein, C. W. Smith, B. T. MacBride, W. H. Matthaeus, M. A. Forman, and J. E. Borovsky, Astrophys J **692**, 684 (2009).

[41] C. Hamilton, K., C. W. Smith, B. J. Vasquez, and R. J. Leamon, J. Geophys. Res., **113, doi:10.1029/2007JA012559**, A01106 (2008).

[42] C. W. Smith, K. Hamilton, and B. J. Vasquez, Astrophys J. **645**, L85 (2006).

[43] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipe* (Cambridge University Press, 1992).

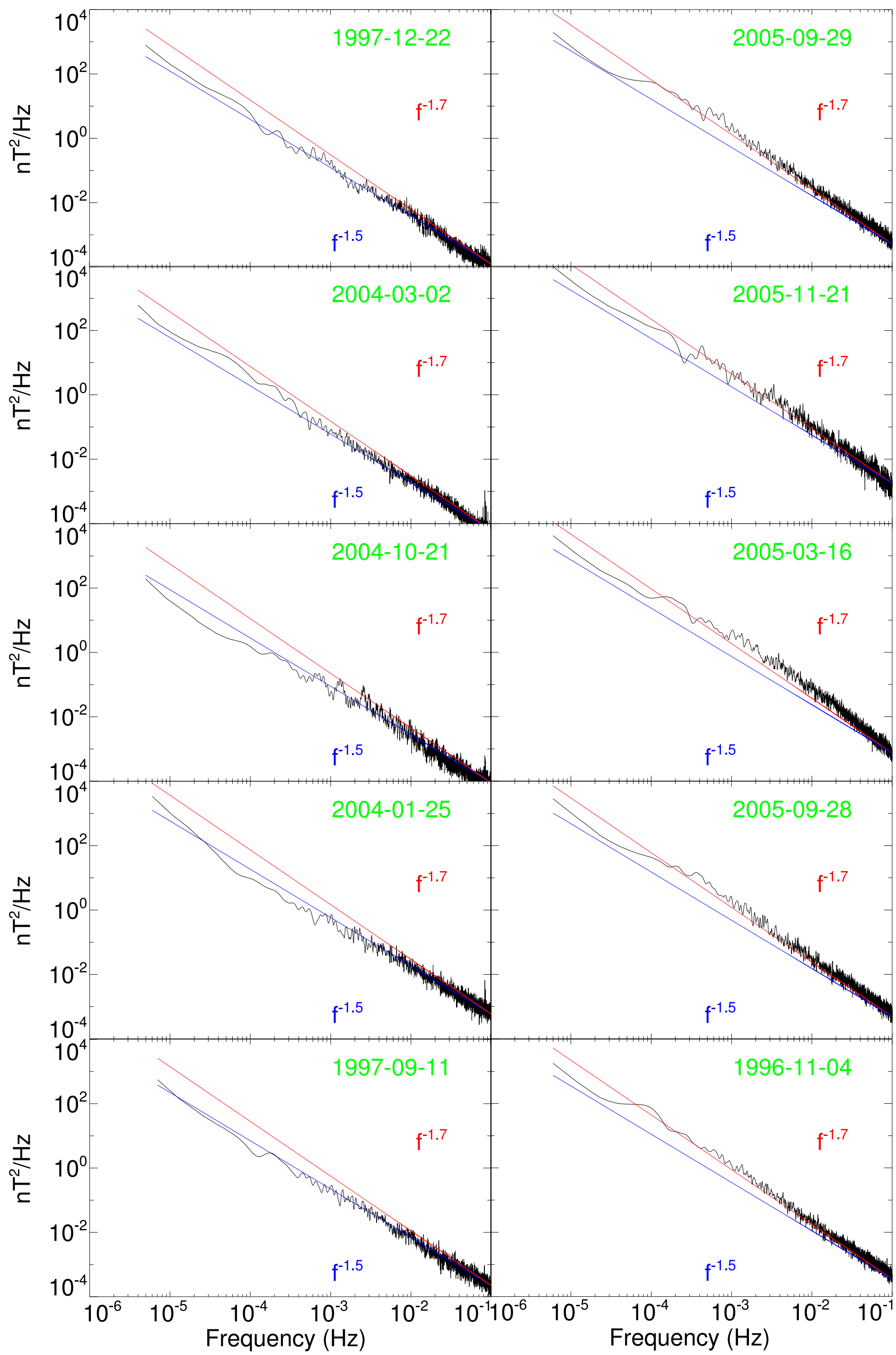

FIG. 1. Power spectra for current-sheet free periods (left) and current-sheet abundant periods (right).