SMALL-SCALE ENERGY CASCADE OF THE SOLAR WIND TURBULENCE

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ABSTRACT

Magnetic fluctuations in the solar wind are distributed according to Kolmogorov’s power law $f^{-5/3}$ below the ion cyclotron frequency $f_{ci}$. Above this frequency, the observed steeper power law is usually interpreted in two different ways, as a dissipative range of the solar wind turbulence, or another turbulent cascade, the nature of which is still an open question. Using the Cluster magnetic data we show that after the spectral break the intermittency increases toward higher frequencies, indicating the presence of nonlinear interactions inherent to a new inertial range and not to the dissipative range. At the same time the level of compressible fluctuations rises. We show that the energy transfer rate and intermittency are sensitive to the level of compressibility of the magnetic fluctuations within the small-scale inertial range. We conjecture that the time needed to establish this inertial range is shorter than the eddy-turnover time, and is related to dispersive effects. A simple phenomenological model, based on the compressible Hall MHD, predicts the magnetic spectrum $\sim k^{-7/3+2\alpha}$, which depends on the degree of plasma compression $\alpha$.

Subject headings: MHD — solar wind — turbulence

1. INTRODUCTION

Solar wind, which is highly turbulent, represents a unique opportunity to investigate turbulence in natural plasmas via in situ measurements (Tu & Marsch 1995; Bruno & Carbone 2005). In nonmagnetized fluids, where the energy injection scale is far from the dissipation one, the intermediate scales (inertial range) are described by the universal power-law Kolmogorov spectrum $k^{-s}$ with $s = 5/3$. This law depends neither on the energy injection nor on the energy dissipation processes.

In the solar wind, and in the interplanetary space in general, the mean free path roughly corresponds to the Sun-Earth distance, and the usual dissipation via collisions is negligible. At the same time, in a magnetized plasma there are a number of characteristic space and temporal scales. Investigating solar wind turbulence at these scales is then a challenging topic from the point of view of basic plasma physics. Here we will focus our discussion on the ion scales, namely the ion inertial length $\lambda_i = c/\omega_{pi}$ and the ion cyclotron frequency $f_{ci} = eB/m_i$. At these scales the fluid-like approximation of plasma dynamics, the usual magnetohydrodynamic (MHD) description, breaks down in favor of a more complex description of plasma.

Solar wind turbulent spectrum of magnetic field fluctuations follows a $\sim f^{-5/3}$ power law below the ion cyclotron frequency $f_{ci}$. For $f > f_{ci}$ the spectrum steepens significantly, but is still described by a power law $f^{-s}$, with $s \in (2-4)$ (Leamon et al. 1998; Smith et al. 2006).

“In situ” solar wind measurements provide time series data, i.e., information on frequency in Fourier space. How does one get any information on wavevectors? For fluctuations with velocities much smaller than the plasma bulk velocity $V$, the Taylor hypothesis is valid: the observed variations on a timescale $\delta t$ correspond to variations on the spatial scale $\delta r = V \delta t$. Therefore, there is a direct correspondence between $f$ and $k$ spectra.

If the solar wind turbulence was a mixture of linear wave modes, the Taylor hypothesis would be well verified only below the spectral break: the bulk velocity is super-Alfvénic ($V > V_A$, where $V_A$ is the Alfvén speed), and so the low-frequency fluctuations can be considered as frozen in plasma. However, whistler waves (with $f > f_{ci}$ and phase speed $V_p > V_A$) do not satisfy the Taylor hypothesis assumption. In this study we assume that in the solar wind there are no whistler waves above the spectral break frequency. This last assumption is supported by results recently obtained in the Earth’s magnetosheath (Mangeney et al. 2006).

Using the Taylor hypothesis, the observed solar wind spectrum below the break is usually attributed to the Kolmogorov spectrum $\sim k^{-5/3}$. Above the spectral break, the spectral steepening, $\sim k^{-3}$, can be interpreted in two different ways. Some authors associate it with the dissipation range (Leamon et al. 1998, 1999, 2000; Bale et al. 2005; Smith et al. 2006). Others suggest that after the spectral break another turbulent cascade takes place (Biskamp et al. 1996; Ghosh et al. 1996; Stawicki et al. 2001; Li et al. 2001; Galtier 2006).

In ordinary fluid flows, the dissipation range is described by an exponential function (Frisch 1995), while in the solar wind, a well-defined power law is observed after the break point and not an exponential. Note that power spectra, i.e., the second-order statistics, completely describe Gaussian, or statistically independent, fluctuations. However, as is well known, fluctuations cannot be described by a Gaussian statistics in the low-frequency part of the solar wind turbulence (Bruno & Carbone 2005). Deviations from Gaussianity, i.e., intermittency (Frisch 1995), may be quantified by the flatness, the forth-order moment of fluctuations.

In this paper we investigate the nature of magnetic fluctuations in the high-frequency range of the solar wind turbulence, which is usually called the dissipation range. We find that in this range the flatness increases with frequency. This is similar to what is going on in the low-frequency range. The presence of intermittency...
together with the well-defined power law in the high-frequency part of the spectrum suggests another turbulent cascade rather than a dissipation range. This small-scale cascade is observed to be much more compressible than the Kolmogorov-like inertial range, in agreement with the previous observations by the Wind spacecraft (Leamon et al. 1998). We show that the energy transfer rate and intermittency are sensitive to the level of compressibility of the turbulent fluctuations in this range. Finally, we propose a simple phenomenological model, based on the compressible Hall MHD, which allows us to explain the observed range of the spectral indices in the high-frequency part of the solar wind spectrum.

2. TURBULENT SPECTRA AND INTERMITTENCY

In the present study we analyze the Cluster magnetic field data up to 12.5 Hz (or 100 kHz). We use 57 minutes of data during the interval 22:35:00–23:32:00 UT on 2001 April 5, when Cluster was in the solar wind not connected to the bow shock. During this period the interplanetary magnetic field was \( B \approx 7 \text{nT} \), the ion density was \( n_i \approx 3 \text{cm}^{-3} \), the plasma bulk velocity was \( V \approx 540 \text{km s}^{-1} \), the ion temperature was \( T_i \approx 33 \text{eV} \), the Alfvén speed was \( V_A = B/(\mu_0 m_i n_i)^{1/2} \approx 7 \text{km s}^{-1} \). The ion skin depth \( \delta_i \) was about 130 km, the ion Larmor radius was \( \rho_i \approx 80 \text{km} \), and the ion plasma beta was \( \beta_i = 2\mu_0 p_i /B^2 \approx 0.8 \), where \( p_i \) represents the pressure of the ions. All the data are from Cluster spacecraft 1, \( B \) is determined from the fluxgate magnetometer (FGM; Balogh et al. 2001), the other plasma parameters are provided by the CIS/HIA instrument (Rème et al. 2001). Magnetic field fluctuations are measured by the search coils (SC) of the STAFF experiment with 0.04 s time resolution (Cornilleau-Wehrlin et al. 2003). This instrument operates in the frequency domain (0.35–12.5 Hz). We use FGM data to resolve the frequencies below 0.35 Hz. Results from Cluster have been compared with data from the Helios 2 satellite within the range (0.001–1)\( f_{ci} \). These data are selected within a high-speed stream \( V \approx 600 \text{km s}^{-1} \), when the satellite orbited at 0.96 AU (Bruno et al. 2003).

In order to analyze the magnetic field fluctuations in the solar wind we use the Morlet wavelet transform, defined as

\[
W_{i}(\tau, t) = \sum_{j=0}^{N-1} B_i(t_j) \psi[(t_j - t)/\tau],
\]

which represents the transform of the \( i \)th component of the magnetic field \( B_i(t_j) \), a data time series with equal time spacing \( \delta t \) and \( j = 0, \ldots, N - 1 \). Here \( \tau \) is a timescale (the corresponding frequency is \( f = 1/\tau \)), while \( \psi(u) = 2^{1/2} \pi^{-1/4} \cos(\omega_0 u) \exp(-u^2/2) \) is the Morlet wavelet, where \( \omega_0 = 6 \). The square of a wavelet coefficient gives a “quantum of energy” of magnetic fluctuations on a scale \( \tau \) at a time \( t \). Thus, we define the power spectral density of \( B_i \) as

\[
S_i(\text{nT}^2/\text{Hz}) = \frac{2\delta t}{N} \sum_{j=0}^{N-1} |W_{i}(\tau, t_j)|^2.
\]

Figure 1 shows the total power spectrum density of the magnetic fluctuations \( S = \sum_{i=1}^{3} S_i \) (solid lines) and the spectrum of magnetic field modulus fluctuations \( \delta |B| \) (dash-dotted lines), which corresponds to the spectrum of parallel fluctuations of magnetic field \( S_{||} \). In agreement with previous observations, the solar wind spectra follow well-defined power laws with a break around \( f_{ci} \approx 0.3 \text{Hz} \), in the vicinity of \( f_{ci} \approx 0.1 \text{Hz} \). Taking into account the Taylor hypothesis, \( f_{ci} \) corresponds to a spatial scale \( Vf_{ci} \approx 1800 \text{km s}^{-1} \) and to the normalized angular wave-number \( k\delta_i \approx 0.4 (k\rho_i \approx 0.3) \). Below the break, the Helios spectrum \( S \sim f^{-1.65} \) is fitted roughly by Kolmogorov’s law. The Cluster FGM spectrum covers a (0.02–0.5) Hz frequency range, the lower resolved frequency here is determined by the length of the considered time period, 57 minutes, and by a cone of influence of the Morlet wavelet transform (Torrence & Compo 1998). Even if the frequency range is not that large, this spectrum can be described by a power law \( S \sim f^{-1.75} \). Above the break, the spectrum follows a \( S \sim f^{-2.6} \) law: the spectral index 2.6 lies in the range (2.4–2.8).

**Figure 1.**—Total magnetic field power spectral density \( S \) and the spectrum of compressible magnetic fluctuations \( S_i \) (dash-dotted line) measured by Helios 2 (up to 0.08 Hz) and by Cluster (up to 12.5 Hz). Straight lines show power-law fits. Vertical dotted lines indicate the ion cyclotron frequency \( f_{ci} \) and the Doppler-shifted ion inertial length \( f_{ci} \).

Let us now consider statistical properties of turbulent fluctuations in the high-frequency part of the spectrum. Figure 2 shows the probability distribution functions (PDFs) of the normalized variables \( b_{\tau}(\tau) = N_{e}(\tau)/\sigma_{\tau} \), with the standard deviation \( \sigma_{\tau} = \sqrt{\langle N_{e}(\tau)^2 \rangle} \), at three different timescales \( \tau \); the dashed lines indicate the corresponding Gaussian fits. Apparently, the smaller the scale the more the PDFs deviate from Gaussian. The PDFs of the other components of the magnetic field present a similar behavior. The dependence of normalized PDFs on scale is a signature of intermittency (Frisch 1995; Bruno & Carbone 2005).

Intermittency may be quantified by the flatness. Figure 3 shows the spectrum of flatness \( F(f) = \langle N_{e}^2 \rangle /\langle N_{e}^2 \rangle \) of \( B_i \) fluctuations. We can see that in the low-frequency part \( F \) increases from the large-scale Gaussian value \( F = 3 \). This means that the usual Alfvénic cascade (Bruno & Carbone 2005) proceeds toward smaller scales, building up phase correlations among fluctuations. In the vicinity of \( f_{ci} \), Helios indicates an increase of the flatness and Cluster/FGM shows a slight decrease. This disagreement may be due to (1) aliasing at the highest frequencies of Helios; (2) artifacts on the FGM at frequencies around the

\[ f_{ci}. \]

\[ f_{ci}. \]
satellite spin frequency 0.25 Hz; or some other physical reasons that are outside of the scope of the present paper. Here we will focus our discussion on the higher frequencies, resolved by Cluster/STAFF-SC, where the flatness again displays a power-law dependence on $f$. This scaling behavior is inherent to nonlinear dynamics and refers to a new kind of "inertial region."

In nonmagnetized fluid, a rapid exponential increase of the flatness is observed in the near-dissipation range, since only the strongest fluctuations survive, while the others are destroyed by viscosity (Chevillard et al. 2005). After such an increase the flatness saturates. In our case, the saturation is not observed, and there is a power-law increase of flatness. At the same time, strong coherent structures that give an important increase of intermittency represent only 2% of the fluctuations at each scale (see the insert of Fig. 3). This estimation has been made using a method proposed by Farge (1992), named the "local intermittency measure" analysis. It consists of separating the intermittent events that contribute to the flatness in the high-frequency part of the spectrum.

3. ROLE OF COMPRESSIBLE FLUCTUATIONS

The results described in §2 suggest that above the spectral break frequency $f_b$ there is a nonlinear compressible cascade and not a dissipation range. In this section we show that the level of the plasma compressibility in this range can be at the origin of a "nonuniversality" of statistics of the magnetic fluctuations. To show this we consider two 7 minute time periods on 2001 April 5, with different ion plasma $\beta_i$.

Figure 4a shows the total power spectrum density of the magnetic fluctuations within the high-frequency range $S$ (solid line), and the spectrum of parallel fluctuations of magnetic field $S_\parallel$ (dash-dotted line) for a time period that starts at 23:03:02 UT, when $\beta_i \approx 0.5$. Figure 4b shows $S$ and $S_\parallel$ for a period starting at
22:35:02 UT, when $\beta_i \simeq 1.5$. The straight lines indicate power-law fits: $S \sim f^{-2.35}$ for the first time period and $S \sim f^{-2.50}$ for the second. Figure 4c shows the ratio $\Delta S_i/S$ for the two considered time periods. One can see that during the first time period (with $\beta_i \simeq 0.5$) the energy of compressible fluctuations is less than 20% of the total energy of the fluctuations (see the solid line), while for the second it is around 30% (see the dashed line). Figure 4d shows the flatness $F(f)$ calculated within the two time periods (here again the solid line corresponds to the period with smaller $\beta_i$, and the dashed line corresponds to the period with higher $\beta_i$).

These observations indicate that for higher $\beta_i$, the level of compressibility increases, leading to a steepening of the magnetic power law and an increase of intermittency. To confirm these results more intervals for wider plasma parameters should be analyzed.

4. NATURE OF THE SMALL-SCALE CASCADE

How can we explain the small-scale energy cascade, which is sensitive to the compressibility of the fluctuations, in the solar wind turbulence? There are several interpretations. Following Schekochihin et al. (2007), at spatial scales between the ion and electron characteristic scales, there is a superposition of (undamped) kinetic Alfvén wave (KAW) and entropy cascades. KAW waves are expected to have low frequencies $f \ll f_i$ and nearly perpendicular wavevectors with respect to the mean field, $k_\perp \gg k_i$.

Another possible explanation of the small-scale cascade is a superposition of nonlinear fluctuations (not waves), which exchange energy on times smaller than the usual eddy-turnover (or nonlinear) time. At spatial scales at the order of $\lambda_i$ and at frequencies of the order of $f_{\omega_i}$, one should take into account the Hall effect in Faraday’s equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left( V \times \mathbf{B} - \frac{m_i}{e\rho} \mathbf{J} \times \mathbf{B} + \eta \mathbf{J} \right),$$

where $\mathbf{J} = e \nabla \times \mathbf{B}/4\pi$ is the current density, and $\eta$ is a scalar dissipation coefficient. This equation contains three different physical processes, with three associated characteristic times. By introducing for each length scale $\ell$ the mean value of density $\rho_i$, magnetic intensity $B_i$, and velocity $u_i$, we can define an eddy-turnover time $T_{NL} \sim \ell/u_i$, a characteristic time associated with the Hall effect $T_H \sim \rho_i \ell^2/B_i$, and a dissipative time $T_D \sim \ell^2/\eta$. At large scales the main effect is given by the term $\nabla \times (V \times B)$, which describes the low-frequency Alfvénic cascade (Bruno & Carbone 2005) realized in a time $T_{NL}$. We conjecture that approaching the scale of the spectral break, $T_H$ appears to be of the order of $T_{NL}$, and beyond the break, the nonlinear energy transfer is realized in a time $\sim T_H < T_{NL}, T_D$.

In a compressible fluid the energy balance equation must be expressed in terms of energy densities (i.e., energy per unit volume) and not in terms of specific energy (i.e., per unit mass), in order to take into account density fluctuations (e.g., see Fleck 1996). The mean volume rate of energy transfer on Hall times in a compressible fluid is therefore

$$\varepsilon_V \sim \frac{\rho_i u_i^2}{T_H}.$$  

Assuming equipartition between kinetic and magnetic energies $\rho_i u_i^2 \sim B_i^2$, the energy-transfer rate is then proportional to

$$\varepsilon_V \sim \frac{B_i^2}{T_H} \sim \frac{B_i^2}{\ell^2 \rho_i}.$$  

Following von Weizsäcker (1951), the ratio of the mass density $\rho$ at two successive levels of the hierarchy is related to the corresponding scale size $\ell$ by the following equation

$$\frac{\rho_\ell}{\rho_{\ell+1}} = \left( \frac{\ell}{\ell_{\nu+1}} \right)^{-3\alpha},$$

where $|\alpha|$ is a measure of the degree of compression at each level $\nu$ (larger $\nu$ meaning larger length scale), and ranges from $\alpha = 0$ for no compression up to $|\alpha| = 1$ for isotropic compression ($3|\alpha|$ is a number of dimensions in which the compression takes place). So, using this density scaling, $\rho_\ell \sim \ell^{-3\alpha}$, and assuming a constant spectrum energy transfer rate we have

$$B_\ell \sim \rho_\ell^{1/3} \ell^{2/3} \sim \ell^{2/3-\alpha}.$$  

Therefore, the spectral energy function is

$$E(k) \sim \frac{\rho_\ell^2}{k} \sim k^{-7/3+2\alpha}.$$  

In the incompressible plasma limit ($\alpha = 0$), this phenomenology predicts a $\sim k^{-7/3}$ spectrum. Such a spectrum has been observed both in direct numerical simulations of an incompressible electron MHD (EMHD) turbulent system (Biskamp et al. 1996) and in the EMHD limit of the incompressible Hall MHD shell model (Galtier & Buchlin 2007).

In the case of isotropic compression toward smaller scales ($\alpha = 1$), which can take place in the interstellar medium, the spectrum is $E(k) \sim k^{-1/3}$. If the isotropic compression is going on toward larger scales ($\alpha = -1$), the spectrum will be $E(k) \sim k^{-13/3}$. In the case analyzed here, the power-law spectrum of magnetic fluctuations follows the $\sim k^{-2.8}$ law, which corresponds to $\alpha \simeq -0.14$, i.e., the scaling relation for the density is $\rho_\ell \sim \ell^{0.4}$.

This simple phenomenological model allows us to explain the variations of the spectral index of the high-frequency part of the solar wind spectrum from $-4$ to $-2$ by different degrees of plasma compression with $\alpha$ between $-5/6$ and $1/6$.

It is worth saying that a better model would take into account (1) the space anisotropy ($k_\perp \neq k_i$) that appears in a plasma with a mean field, and (2) possible different scaling for velocity and magnetic field that can be found in the compressible Hall MHD (Servidio et al. 2007). However, the interpretation of the small-scale energy cascade in the Hall MHD frame is supported by the observations of a clear correlation between the spectral break frequency $f_b$ and the Doppler-shifted wavevector of the ion inertia length $f_b$ (Leamon et al. 2000).

Note that the solar wind spectral break frequency $f_b$ is usually observed to be lower than $f_j$ (Leamon et al. 1998). This can be explained by the fact that the Hall effect starts acting at scales larger than $\lambda_i$. In our case, for example, $f_b/f_j \approx 0.1$, and the scale of the spectral break is $\sim 10 \lambda_i$.

Introducing the Hall-Reynolds number as the ratio of the nonlinear term over the Hall term

$$R_H \sim \frac{e}{c m_i} \frac{\rho_i u_i \ell}{B_i},$$

one can see that $R_H \approx 1$ (i.e., $T_{NL} \approx T_H$) at a scale $\ell$, which is not necessarily equal to $\lambda_i$,

$$\frac{\ell}{\lambda_i} = \frac{4 \pi V_{Al} u_i}{u_e}.$$
where $V_A$ and $\lambda_{a i}$ are the mean values of the Alfvén speed and the ion inertial length at scale $\ell$, respectively.

5. CONCLUSION

In this paper we investigated small-scale turbulent fluctuations in the solar wind (i.e., at frequencies above the spectral break at the vicinity of $f_\omega$). Taking into account the Taylor hypothesis ($\ell = V/f$), the frequency domain above the spectral break covers $\sim 40-2000$ km space scales that correspond to $(0.3-15)\lambda_i$. In this range we found evidence for strong departure from Gaussian statistics and the presence of intermittency, while the spectrum presents a well-defined power law. Both the presence of a power-law spectrum and the absence of global self-similarity seems to be quite in contrast to the role of “dissipative range.”

In usual fluid turbulence, the dissipative range (Frisch 1995) starts with a rough exponential cutoff; in the near dissipation range the intermittency increases as far as the Gaussian fluctuations dissipate faster than the coherent structures (Chevillard et al. 2005); then the fluctuations become self-similar, the singularities being smoothed by dissipation. In the solar wind turbulence we observe a completely different picture. After the spectral break in the vicinity of $f_\omega$, the flatness increases as a power law, indicating that nonlinear interactions are at work to build up a new inertial range.

This small-scale cascade is much more compressible than the lower frequency Alfvénic cascade. This sudden change in nature of the turbulent fluctuations can happen due to a partial dissipation of magnetic fluctuations at the spectral break: the left-hand Alfvénic fluctuations with $k_\parallel \gg k_\perp$ are damped by the ion cyclotron damping (Ghosh et al. 1996). Above the break, however, a new “magnetosonic cascade” takes place up to the electron characteristic scales. This energy cascade seems to be dominated by fluctuations with $k_\perp \gg k_\parallel$ (Sahraoui et al. 2006; Mangeney et al. 2006).

We found, as well, that the plasma compressibility controls the statistics of the magnetic field fluctuations. Preliminary results show that the increase of the level of the plasma compressibility leads to the spectrum steepening and increase of the intermittency.

To explain this small-scale compressible cascade we introduce here, for the first time, a simple phenomenological model based on the compressible Hall MHD: we find that the magnetic energy spectrum follows a $E(k) \sim k^{-7/3 + 2\alpha}$ law, depending on the degree of plasma compressibility $\alpha$. While far from a complete model of small-scale turbulence, this simple model can explain observed variations of the spectral index within the high-frequency part of the solar wind turbulent spectrum (Leamon et al. 1998; Smith et al. 2006) by different degree of plasma compressibility.

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