SPECTRAL SLOPE VARIATION AT PROTON SCALES FROM FAST TO SLOW SOLAR WIND

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ABSTRACT

We investigated the behavior of the spectral slope of interplanetary magnetic field fluctuations at proton scales for selected high-resolution time intervals from the WIND and MESSENGER spacecraft at 1 AU and 0.56 AU, respectively. The analysis was performed within the profile of high-speed streams, moving from fast to slow wind regions. The spectral slope showed a large variability between $-3.75$ and $-1.75$ and a robust tendency for this parameter to be steeper within the trailing edge, where the speed is higher, and to be flatter within the subsequent slower wind, following a gradual transition between these two states. The value of the spectral index seems to depend firmly on the power associated with the fluctuations within the inertial range; the higher the power, the steeper the slope. Our results support previous analyses suggesting that there must be some response of the dissipation mechanism to the level of the energy transfer rate along the inertial range.

Key words: interplanetary medium – magnetic fields – plasmas – solar wind – turbulence – waves

Online-only material: color figures

1. INTRODUCTION

Typical timescales of solar wind plasma and magnetic field fluctuations extend over several decades, from the Sun’s rotation period down to the smallest scales of the order of ion and electron gyroperiods. The corresponding power density spectrum is characterized by at least three different frequency regions. The lowest frequency range, corresponding to fluctuations of the large scales containing energy, is characterized by a spectral index of the kind $f^{-1}$ (Matthaeus & Goldstein 1986; Dmitruk et al. 2004), whose origin is still debated. A spectral break separates this range from a typical turbulence spectrum, as first shown by Coleman (1968). In particular, Salem (2000), Podesta et al. (2007), and Salem et al. (2009) found that the power-law exponents of velocity and magnetic field fluctuations, at odds with expectations, often have values near the Iroshnikov–Kraichnan scaling of $-3/2$ and the Kolmogorov scaling of $-5/3$, respectively. However, as remarked by Roberts (2007), VOYAGER observations of the velocity spectrum have demonstrated a likely asymptotic state in which the spectrum steepens toward a spectral index of $-5/3$, finally matching the magnetic spectrum and the theoretical expectation of Kolmogorov turbulence. The spectral break cited above was found to shift to lower and lower frequencies with increasing radial distance from the Sun, that is, with increasing age of the turbulence (Bruno & Carbone 2013), suggesting that larger and larger scales are continuously involved in the turbulent dynamics, which transfers energy from larger to smaller scales to be eventually dissipated at kinetic scales. As a matter of fact, around the proton scales, either the proton inertial length or the proton Larmor radius, there is another spectral break beyond which the spectrum generally steepens. This part of the spectrum is commonly called the “dissipation range,” in analogy to hydrodynamics, although the nature of this high-frequency part of the interplanetary fluctuations is still largely debated (Alexandrova et al. 2013; Bruno & Carbone 2013). It was recently shown (Bruno & Trenchi 2014) that this break also shifts to lower frequencies as the wind expands. In particular, the same authors showed that the radial dependence of the corresponding wavenumber, of the kind $k_{sh} \sim R^{-1.08}$, is in good agreement with that of the wavenumber derived from the linear resonance condition for proton cyclotron damping (Marsh et al. 2003; Gary & Borovsky 2004; Marsch 2006, and references therein). Less clear is the value of the spectral index to be associated with this frequency range. As a matter of fact, Smith et al. (2006) performed a wide statistical study on the spectral index in the dissipation range using about 900 intervals of the interplanetary magnetic field recorded by the Advanced Composition Explorer (ACE) spacecraft at 1 AU. These authors found that, while within the inertial range the distribution of the values of the spectral index was quite narrow and peaked between $-5/3$ and $-3/2$, that corresponding to the dissipation range was quite broader, spanning from $-1$ to $-4$ with a broad peak between $-2$ and $-3$. They also found that the dissipation range power-law index at 1 AU strongly depends on the overall fluctuation levels of the interplanetary magnetic field and, consequently, on the rate of the energy cascade. In fact, Smith et al. (2006) estimated the energy cascade rate $\epsilon$ for all the events they studied and found a clear correlation, with the steepest dissipation range spectra associated with the highest cascade rate. In particular, they found that the spectral index varies with the energy cascade rate $\epsilon$ following $\sim -1.05 \epsilon^{0.09}$. These conclusions support previous results by Leamon et al. (1998), who found a positive correlation between the steepness of the spectral index in the dissipation range and the thermal proton temperature, suggesting that steeper dissipation range spectra imply greater heating rates. Markovskii et al. (2006) found that turbulence spectra often have power-law dissipation ranges with an average spectral index of $-3$ and suggested that this fact is a consequence of a marginal state of the instability in the dissipation range. However, they concluded that their mechanism, acting together with Landau damping, would produce an entire range of spectral indices, not just $-3$, in better agreement with the observations.

On the other hand, a different view (Biskamp et al. 1996; Ghosh et al. 1996; Stawicki et al. 2001; Galtier & Buchlin 2007) suggests that beyond the spectral break another turbulent cascade develops. Alexandrova et al. (2008), based on results
obtained studying CLUSTER magnetic field observations in the solar wind, suggested that just beyond the frequency break there is another nonlinear compressible cascade rather than a dissipation range. These authors introduced a phenomenological model based on the compressible Hall MHD and the assumption of kinetic and magnetic energy equipartition that was able to reproduce the non-universality of the spectral slope in the dissipation range by simply taking into account the effects of plasma compressibility. In this way, the complete range of variability of the spectral index found by Leamon et al. (1998) could be recovered.

However, stimulated by recent results by Bruno & Trenchi (2014) supporting the fact that a cyclotron-resonant dissipation mechanism that involves the active role of Alfvenic fluctuations must participate in the spectral cascade, we looked at the behavior of this high-frequency part of the spectrum, examining different regions of high-speed streams, since, moving from fast wind to slow wind across the rarefaction region, both the Alfvenicity and the amplitude of the fluctuations greatly change (Bruno & Carbone 2013).

2. DATA ANALYSIS AND RESULTS

In this Letter, we used observations by WIND at the Lagrangian point L1 and by MESSENGER in the inner heliosphere. Magnetic field measurements were performed by magnetic field investigation (Lepping et al. 1995) on board WIND at \( \sim 11 \text{ Hz} \) and by MAGnetometer (Anderson et al. 2007) on board MESSENGER at 20 Hz, while solar wind experiment (Ogilvie et al. 1995) on board WIND was used for plasma measurements. All the time intervals used in this analysis are listed in Table 1.

We examined several high-speed streams observed by WIND, characterized by a smooth and gradual variation in the solar wind speed in the rarefaction region, from fast to slow wind. Within these regions, we studied the evolution of the magnetic field fluctuations, looking at the total power spectral density (PSD) derived from a trace of the spectral matrix obtained using a Fast Fourier Transform. Leakage effects were mitigated by a Hanning windowing and a 33 point moving average was applied to obtain the spectral estimates.

Figure 1(a) shows the speed profiles for three of these streams observed by WIND in 2011. The gray shading highlights the regions of interest. Each was divided into adjacent sub-intervals of 219 points, corresponding to approximately 13 hours, and for each of them we computed the total PSD of the magnetic field fluctuations. For the sake of clarity, we show only some of these spectra in panels (b)–(d), respectively. Different colors refer to different time intervals whose starting time and corresponding wind speed are listed in each panel.

As expected, the PSD is generally higher within the high-speed wind and gradually decreases in the rarefaction region.

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**Table 1**

| Interval | s/c | \( R \) (AU) |
|----------|-----|------------|
| 2011, 121.500–129.558 | WIND | 0.99 |
| 2011, 175.000–181.558 | WIND | 0.99 |
| 2011, 241.000–245.558 | WIND | 0.99 |
| 2010, 182.000–189.558 | MESSENGER | 0.56 |
| 2010, 182.000–182.038 | MESSENGER | 0.56 |
| 2010, 183.576–183.614 | MESSENGER | 0.56 |
| 2010, 186.628–186.666 | MESSENGER | 0.56 |

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Figure 1. Panel (a): wind speed profile of three different high-speed streams observed by WIND at 1 AU. Panels (b), (c), and (d) show a selection of magnetic field spectra obtained along the speed profile of fast streams (1), (2), and (3), respectively, within the time intervals indicated by the shaded areas. (A color version of this figure is available in the online journal.)
Moreover, within the selected intervals, plasma is hotter and fluctuations have a stronger Alfvénic character dominated by outward modes where the wind speed is higher (not shown).

While at lower frequencies all the spectra have a similar slope, close to the $-5/3$ typical of Kolmogorov scaling, at higher frequencies, above the spectral break observed around 0.3–0.4 Hz, we find a large variability (Leamon et al. 1998; Smith et al. 2006). Steeper spectral slopes are generally observed in high-speed wind and are associated with higher PSDs in the inertial range. On the contrary, going toward the slow wind, the spectral slope gradually decreases down to a quasi-disappearance of the spectral break.

To check whether this behavior was consistent also with observations in the inner heliosphere, we analyzed MESSENGER’s data during the radial alignment with WIND that occurred in 2010 July, when MESSENGER was at 0.56 AU from the Sun (Bruno & Trenchi 2014). During this alignment, WIND observed a transition from fast to slow wind (Figure 2(a)) between June 30 and July 8. The radial alignment between the two spacecraft allowed us to identify the corresponding time interval in MESSENGER’s magnetic field data, evaluating the transit time from one spacecraft to the other on the basis of the wind speed measured by WIND. The possibility of identifying in MESSENGER’s data large-scale magnetic field features similar to those observed in WIND’s data made us confident about the data selection of MESSENGER, which observed the same transition from fast to slow solar wind approximately one day before (Bruno & Trenchi 2014).

The methodology used to study this event with WIND is the same as described above; the analyzed time interval is shown in Figure 2(a) and several spectra computed within this time interval are shown in panel (b). Also, in this case, the analysis confirms that the spectral slope above the frequency break is strongly related to the wind speed and most likely depends on the power associated with fluctuations within the inertial range.

In the case of MESSENGER, the high-resolution (20 Hz) magnetic field data were available only for short periods. With this limitation, we evaluated spectra during the three time intervals of $2^{16}$ points listed in Table 1 and indicated by the yellow shadings in Figure 2(a). The corresponding spectra are shown in panel (b). The average speed values corresponding to these PSDs are deduced from those measured by WIND. MESSENGER strikingly confirms the spectral steepening observed by WIND at 1 AU beyond the spectral break that for MESSENGER is shifted to higher frequencies (Bruno & Trenchi 2014).

In order to relate in some analytical form the observed spectral slope at ion scales to the PSD observed in the inertial range, we report our observations in Figure 3 for all 56 spectra examined in this work, plotting the spectral slope at ion scales as a function of the normalized power (see below) in the inertial range at 1 AU. MESSENGER’s observations at 0.56 AU are also included in this figure after extrapolation to 1 AU of the estimated PSD, assuming a WKB-like radial dependence (Hollweg 1973; Zhou & Matthaeus 1989) as discussed below.

An estimate of the power is obtained as the integral of the PSD in a frequency range chosen within the inertial range. For WIND’s spectra, this frequency range is from $7 \times 10^{-3}$ to $10^{-1}$ Hz, while for MESSENGER’s spectra, we integrated the PSDs in the $2 \times 10^{-2}$ to $2 \times 10^{-1}$ Hz range.

At lower frequencies, it was necessary to choose a different limit for MESSENGER’s spectra, since these spectra were evaluated within shorter data intervals. Also, the upper limit was chosen at a higher frequency because of the frequency shift of the spectral break observed in the inner heliosphere (Bruno & Trenchi 2014).

Subsequently, we estimated the power that MESSENGER’s spectra should have in the same frequency band of WIND by fitting the PSDs with a power law of the kind $f^{-5/3}$. Afterward, we extrapolated these values to 1 AU, assuming the standard $R^{-3}$ radial dependence predicted by WKB theory.
Having noticed that, at 1 AU, the power spectra corresponding to the lowest speed are approximately at the same low level regardless of the time interval under consideration, we normalized the values of the integrated PSD to the same lowest power in the inertial range obtained throughout our analysis. This value refers to the low-speed wind observed by WIND on 2010 July 8. This normalization was applied just to have a dimensionless parameter on the X axis of the plot in Figure 4.

The spectral slopes in the “dissipation range” were obtained through a fitting procedure, taking care to not include regions too close to the break point or at higher frequencies where the spectrum flattens out (Bruno & Trenchi, 2014).

The dependence of the spectral slopes in the dissipation range on the power level in the corresponding inertial range, shown in Figure 3, is rather robust since the same kind of relationship applies equally well to data points belonging to different time intervals indicated by different colors in the plot. The best fit was obtained using a power-law fit, shown by the continuous black line, of the kind:

\[
    q = (-4.37 \pm 0.48) + (2.46 \pm 0.45)w/w_0^{(-0.30 \pm 0.10)},
\]

where \( q \) is the spectral index and \( w/w_0 \) indicates the normalization process performed within the inertial range. It is interesting to note that Equation (1) provides an upper limit for the slope in the dissipation range of 4.37, which is very close to the steepest slopes observed in previous studies (Smith et al., 2006). In particular, in Figure 3 of Sahraoui et al. (2010), those authors show spectral behavior around the frequency break that is remarkably similar to what we found within our fast wind streams. Finally, the dependence we found on the wind speed also implied a dependence on the plasma \( \beta \), which varied between 0.7 and 1.7 (not shown). Thus, lower values of \( \beta \) are associated with faster wind and steeper spectral indexes.

\[ \beta \]

\[ (1) \]

\[ \text{Hollweg, 1973.} \]

\[ \text{Bruno, Trenchi, & Telloni} \]

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\[ \text{WIND's spectra shown in Figure 1(c) are extended into the dissipation range, adopting spectra from THEMIS-C search-coil observations at 128 Hz. (A color version of this figure is available in the online journal.)} \]

\[ \text{2.1. Noise Due to the Digitization Process} \]

One should be careful while analyzing fluxgate magnetometer data at frequencies that might be influenced by ring noise due to the digitization process (Russell, 1972; Lepping et al., 1995; Smith et al., 1998; Alexandrova et al., 2013) and, in general, by the sensor noise as shown by Howes et al. (2008). Bennett (1948) derived the PSD of a uniformly quantized Gaussian random process. He showed that a uniform quantizer \( q \) characterized by a quantization step \( \delta \) produces an average distortion \( \Delta(q) \sim \delta^2/12 \). If we evenly spread this digital noise across the frequency band 0 to the Nyquist frequency \( f_N \), the power density level expected for the digitization noise \( W(\delta) \) would be \( W(\delta) \sim \delta^2/(12 f_N) \). Thus, using this expression and knowing the quantization step \( \delta \), we can estimate the spectral level due to quantization in the cases of MESSENGER and WIND, respectively.

In the case of MESSENGER (Figure 2), the spectral flattening above roughly 3 Hz gives an average spectral density higher than the lowest detectable power associated with a digitization step size of 0.047 nT (Anderson et al., 2007), which would be around \( 1.8 \times 10^{-5} \text{nT}^2 \text{Hz}^{-1} \). However, as shown by Anderson et al. (2007), the lower detection limit \( W(\delta) \) is not a comprehensive measure of the entire high-frequency noise due to digitization. This level was estimated (Anderson et al., 2007) to be around \( 2.5 \times 10^{-4} \text{nT}^2 \text{Hz}^{-1} \) and it is clearly visible also in our spectra relative to MESSENGER (see Figure 2) at frequencies larger than 2–3 Hz. In any case, being at much lower level cannot determine the less steep slope observed just beyond the spectral break already visible in the second spectrum from the top (light blue).

Similar evaluations would suggest that the lowest detectable power associated with the digitization step size in the case of WIND (Lepping et al., 1995) would be around \( 1.7 \times 10^{-5} \text{nT}^2 \text{Hz}^{-1} \), assuming a digital step of 0.032 nT. However, also in this case, the digitization noise level flattens out the spectra at a level of roughly \( 5 \times 10^{-4} \text{nT}^2 \text{Hz}^{-1} \) for frequencies beyond 2 Hz (see Figure 1).
As further proof of the reliability of our spectral estimates at ion scales, we analyzed data from the search-coil magnetometer on board THEMIS-C (Roux et al. 2008) during the same stream of 2011 June observed by WIND and obtained solar wind speed values from the plasma sensor (McFadden et al. 2008). During part of the duration of this stream, THEMIS-C was in the solar wind not connected to the Earth’s bow shock. These spectra, based on 128 Hz sampling frequency, are shown together with WIND’s spectra in Figure 4 and unravel the behavior of these spectra within the next frequency decade or so. The length of each data sample varied between 213 and 215 data points and the relative starting time is shown in the same figure. Frequency spikes, due to the fact that data have not been de-spun, have been removed artificially from the graph, leaving unaltered the general behavior of the spectra, which satisfactorily match WIND’s spectra at 3Hz and show that the power level, at these scales, is independent of whether the spectrum refers to fast or slow wind. The average value of the spectral index between 3 and 50 Hz for the analyzed periods is $-2.36 \pm 0.11$.

3. SUMMARY AND CONCLUSIONS

We investigated the behavior of the spectral slope at proton scales, up to frequencies of a few Hz, beyond the high-frequency break separating fluid from kinetic scales. We used high time resolution interplanetary magnetic field data from WIND and MESSENGER spacecraft at 1 AU and 0.56 AU, respectively. Several time intervals were selected whenever long enough samples of high-resolution data were available within high-speed streams and the following rarefaction regions down to the slow wind. In particular, we avoided analyzing those regions of slow wind characterized by strong compressive phenomena due to the dynamical interaction between fast and slow wind and showing a clear lack of time stationarity. One of these selected events corresponded to a radial alignment between the two spacecraft already studied by Bruno & Trenchi (2014). We found a large variability of the spectral slope, as already reported in the literature (Leamon et al. 1998; Smith et al. 2006), between $-3.75$ and $-1.75$. However, we also found a robust tendency of this parameter to show the steepest spectra within the trailing edge of the fast streams, where the speed is higher, and the lowest values within the subsequent slow wind, following a gradual transition between these two states. The value of the spectral index seems to depend firmly on the power characterizing the fluctuations within the inertial range; the higher the power, the steeper the slope. In particular, this slope tends to approach $-5/3$ within the slowest wind and a limiting value of $-4.37 \pm 0.48$ within the fast wind.

Our results support previous analyses (Smith et al. 2006) suggesting that there must be some response of the dissipation mechanism related to the energy transfer rate along the inertial range. Generally, fluctuations within faster wind not only have larger amplitudes but are also more Alfvénic. It would be interesting to understand whether the spectral slope in this high-frequency range depends solely on the power level of the fluctuations or also on their Alfvénic character, i.e., on the cross-helicity. In any case, average values of the spectral index at proton scales, based on statistical studies employing a large data set, would depend on the relative amount of fast and slow wind present in the data set itself. In this respect, the same analysis performed for different phases of the solar cycle, characterized by a different amount of fast wind in the ecliptic, could produce contradictory results that would merely depend on an unbalanced presence of fast and slow wind.

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