RADIAL DEPENDENCE OF THE FREQUENCY BREAK BETWEEN FLUID AND KINETIC SCALES IN THE SOLAR WIND FLUCTUATIONS

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ABSTRACT
We investigate the radial dependence of the spectral break separating the inertial from the dissipation range in power density spectra of interplanetary magnetic field fluctuations, between 0.42 and 5.3 AU, during radial alignments between MESSENGER and WIND for the inner heliosphere and between WIND and ULYSSES for the outer heliosphere. We found that the spectral break moves to higher and higher frequencies as the heliocentric distance decreases. The radial dependence of the corresponding wavenumber is of the kind \( k_b \sim R^{-1.08} \), in good agreement with that of the wavenumber derived from the linear resonance condition for proton cyclotron damping. These results support conclusions from previous studies which suggest that a cyclotron-resonant dissipation mechanism must participate in the spectral cascade together with other possible kinetic noncyclotron-resonant mechanisms.

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

Online-only material: color figures

1. INTRODUCTION
Solar wind fluctuations show a typical Kolmogorov inertial range extending over several frequency decades. This range is bounded at low frequency by a knee separating the \( k^{-5/3} \) from the \( k^{-1} \) scaling, which is typical of the large-scale energy containing eddies. The origin of this \( k^{-1} \) scaling is still obscure in spite of the fact that many attempts have been made to explain the physical mechanism governing this behavior (Matthaeus & Goldstein 1986; Dmitruk & Matthaeus 2007; Verdini et al. 2012). This frequency break moves to ever larger scales as the wind expands (Bruno & Carbone 2013). This has been interpreted as evidence that non-linear processes are at work governing the evolution of solar wind fluctuations (Tu & Marsch 1992). The radial dependence of this break shows a power law of the order of \( R^{-1.5} \) (Bruno & Carbone 2013) for fast ecliptic wind and \( R^{-1.1} \) for fast polar wind (Horbury et al. 1996), suggesting that the turbulence evolution in the polar wind is slower than in the ecliptic, as expected (Bruno 1992; Grappin et al. 1991).

Not far from the local cyclotron frequency, there is another spectral break (see review by Alexandrova et al. 2013) which marks the beginning of the region where kinetic effects must be considered (Leamon et al. 1998b). Within this region, for about one decade the spectral index steepens toward values roughly between \(-3\) and \(-4\) (Leamon et al. 1998b). At these scales (see reviews by Gary 1993 and Marsch 2006), a perpendicular proton temperature remarkably higher that the parallel one and a temperature radial dependence much slower that the proton inertial length can also be expressed as \( \lambda_i = v_A/\Omega_p \), where \( v_A = B/(4\pi nm_p)^{1/2} \) is the Alfvén speed.

The role of \( \lambda_i \) becomes relevant for two-dimensional (2D) turbulence dissipation which, through the turbulence reconnection process, tends to generate current sheets along the magnetic field and strong field fluctuations in the transverse direction. Dmitruk et al. (2004) showed that these magnetic structures, of the order of the proton inertial length, strongly energize protons in the transverse direction due to the induced electric field experienced by the particles moving at the plasma MHD velocity.

The same \( \lambda_i \) can be associated with another process that is able to steepen the spectrum without involving dissipation: the Hall effect. This effect becomes relevant at kinetic scales shorter than the ion inertial length and at timescales shorter than the proton cyclotron period (Galtier 2006; Smith et al. 2006; Galtier & Buchlin 2007). This effect operates by modifying the nonlinear interactions between different eddies and generating a turbulent cascade of energy beyond the proton inertial scale, as shown by Alexandrova et al. (2008).

Moreover, for typical values of solar wind plasma \( \beta \), as soon as \( k\lambda_i \) of Alfvén cyclotron waves approaches scales comparable with the proton inertial length \( \lambda_i \), cyclotron resonance and damping are quickly activated (Gary & Borovsky 2004).

On the other hand, \( \lambda_L \) is invoked for damping kinetic Alfvén waves (KAWs) propagating at large angles with respect to the local mean field (Howes et al. 2008; Leamon et al. 1998b, 1999).

Leamon et al. (1998a) then postulated a balancing between cyclotron-resonant and noncyclotron-resonant dissipation effects able to transfer energy cascading from the MHD range

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of scales into the dissipation range. The cyclotron-resonant part of this mechanism was able to account for the left-handed magnetic helicity signature often found in the dissipation range (He et al. 2011).

However, Markovskii et al. (2008) concluded that none of the available models was able to reproduce the exact location of the break observed at 1 AU by ACE and suggested that the position of the spectral break is determined by a combination of the scale of the turbulent fluctuations and their amplitude at that scale.

Sahraoui et al. (2009) reported the first evidence of the cascade of turbulence below the proton gyroscale $\lambda_p$ and its dissipation at the electron gyroscale via collisionless electron Landau damping, showing that turbulence made of highly oblique KAWs could account for the observations.

Alexandrova et al. (2009) clearly distinguished the different roles of the different spatial kinetic plasma scales and showed that the electron Larmor radius represents the dissipation scale of magnetic turbulence in the solar wind, but could not exclude that at the ion and electron cyclotron frequencies there might be some dissipation by cyclotron damping.

Chen et al. (2012) found the same steep spectral index (about $-2.75$) for magnetic and density fluctuations between ion and electron scales. This spectral index, which is steeper than expected for a strong turbulence dispersive cascade which predicts $-7/3$ (Biskamp et al. 1996), as for a pure whistler or KAW cascade, is consistent with damping of some of the turbulent energy at these scales or with increased intermittency, since both density and magnetic fluctuations become organized in highly intermittent, 2D structures (Boldyrev & Perez 2012; Alexandrova et al. 2013).

Alexandrova et al. (2012) found that the high-frequency steepening of the spectra, when the magnetic field is sampled at large angles, was nicely fitted by $E(k_{\perp}) \propto k_{\perp}^{-8/3} \exp(-k_{\perp}^2/\rho_e^2)$, $k_{\perp}$ and $\rho_e$ being the perpendicular wavenumber component and the electron Larmor radius, respectively, and the amplitude of the spectrum $A$ was the only free parameter of this model. Their results were compatible with Landau damping of magnetic fluctuations at electron scales.

Bourouaine et al. (2012) analyzed magnetic field spectra between 0.3 and 0.9 AU and, assuming a dominant 2D nature of the turbulent fluctuations, found a better agreement between the spatial scale corresponding to $f_b$ and the proton inertial scale $\lambda_i$ rather than the proton gyroradius scale $\lambda_p$. However, Bourouaine et al. (2012) remarked that while $\lambda_i$ and $\lambda_p$ varied with distance as expected, $f_b$ remained almost constant, varying only between 0.2 and 0.4 Hz. These findings were in agreement with previous results obtained by Perri et al. (2010) who analyzed the radial evolution of $f_b$. These authors took several time intervals from ULYSSES observations during fast wind and magnetic field observations from MESSENGER when the $s/c$ was at 0.3 and 0.5 AU, but they could not determine the solar wind conditions during the intervals they analyzed because of the lack of plasma observations.

Since the largest variations of the solar wind parameters happen to be within the inner heliosphere, special care is required when selecting time intervals at different heliocentric distances in order to analyze, as far as possible, the same type of wind, either fast or slow (Bruno & Carbone 2013). Conscious of this caveat, we again analyzed the radial dependence of $f_b$, trying to select whenever possible $s/c$ alignments during fast wind in order to observe the same plasma at different heliocentric distances.

## 2. DATA ANALYSIS AND RESULTS

We used observations by MESSENGER in the inner heliosphere, WIND at the Lagrangian point L1, and ULYSSES in the outer heliosphere. The overall radial excursion ranged between 0.42 and 5.3 AU as shown in Table 1. We selected eight intervals, two in the inner heliosphere, three at 1 AU, and three in the outer heliosphere. Six out of the eight intervals were chosen during radial alignments between MESSENGER and WIND and between WIND and ULYSSES. Magnetic field measurements were performed by MAG (Anderson et al. 2007) on board MESSENGER at 20 Hz, by MFI (Lepping et al. 1995) on board WIND at $\sim$11 Hz, and by MAG (Balogh et al. 1992) on board ULYSSES at 1 Hz. We used magnetic data at much higher sampling rates than those used by previous similar analyses (Perri et al. 2010; Bourouaine et al. 2012). This result proved to be extremely important, since at short heliocentric distances we found that the breakpoint moves to frequencies around 1 Hz. Plasma measurements were performed by SWE (Ogilvie et al. 1995) on board WIND and by SWOOPS (Bame et al. 1992) on board ULYSSES. Plasma parameters from MESSENGER are not available but they were inferred during the alignments with WIND as we discuss below.

The first alignment occurred during 2010 (Table 1), when MESSENGER was cruising toward Mercury and was 0.56 AU from the Sun. WIND and MESSENGER remained almost aligned from day of year (DOY) 180 to 197, when the relative separations in longitude and latitude were smaller than 10° and 6°, respectively. WIND observed a fast stream from DOY 181 to 185. Using the average wind speed of about 620 km s$^{-1}$ we identified the corresponding time interval in MESSENGER’s magnetic field data, taking into account the transit time from one $s/c$ to the other. To cross check the validity of this operation, we identified in MESSENGER’s data similar magnetic field features observed in WIND’s data. To estimate plasma parameters

### Table 1

| Interval | $s/c$ | $R$ (AU) | $B$ (nT) | $n$ (cm$^{-3}$) | $V_{sw}$ (km s$^{-1}$) | $T$ (K) | IR | DR | $f_b$ (Hz) | $\theta_{IR}$ (°) |
|----------|------|---------|---------|---------------|----------------------|--------|----|----|-----------|------------------|
| 2011, 100.87–101.03 | MESS | 0.42 | 21.53 | (22.58) | (586) | (670581) | −1.58 | −2.90 | 0.848 ± 0.008 | 11.8 |
| 2010, 182.04–182.65 | MESS | 0.56 | 6.28 | (6.25) | (604) | (218382) | −1.58 | −3.72 | 0.534 ± 0.003 | 24.7 |
| 2010, 182.83–183.95 | WIND | 0.99 | 3.89 | 1.96 | 604 | 140390 | −1.65 | −3.26 | 0.331 ± 0.002 | 46.3 |
| 2011, 102.65–102.78 | WIND | 0.99 | 5.93 | 3.98 | 586 | 327533 | −1.64 | −3.17 | 0.387 ± 0.003 | 20.7 |
| 2007, 239.12–240.24 | WIND | 0.99 | 4.81 | 2.58 | 632 | 242000 | −1.69 | −3.45 | 0.409 ± 0.002 | 38.7 |
| 2007, 201.77–204.29 | ULYSS | 1.4 | 2.14 | 1.25 | 560 | 107162 | −1.76 | −3.58 | 0.192 ± 0.001 | 27.0 |
| 2000, 192.96–193.34 | ULYSS | 3.2 | 0.737 | 0.216 | 732 | 74060 | −1.74 | −2.59 | 0.096 ± 0.003 | 49.0 |
| 1992, 235.92–236.30 | ULYSS | 5.3 | 0.412 | 0.087 | 766 | 48322 | −1.68 | −2.59 | 0.065 ± 0.005 | 52.2 |
Figure 1. Panels (A) and (B): magnetic field PSD relative to the MESSENGER and WIND alignments during 2010 and 2011, respectively. Panel (C): magnetic field PSD, in the same format as the upper panels, for the WIND and ULYSSES alignment during 2007. Vertical dashed lines indicate frequency breaks (see text for details). White circles indicate the boundaries of the frequency ranges adopted to estimate the relative spectral slope.

Figure 2. Summary plot of magnetic field spectral densities relative to the time intervals shown in the previous figure (for simplicity, only the WIND 2010 interval is shown here) and to two additional time intervals recorded by ULYSSES at 3.2 and 5.3 AU. Spectral breaks are indicated by vertical dashed lines and reported in Table 1. White circles indicate the boundaries of the frequency ranges adopted to estimate the relative spectral slope.

at MESSENGER’s location, we back projected WIND’s observations to 0.56 AU using $R^{-2}$ for the density and $R^{-0.762}$ for the temperature, with $R$ being the heliocentric distance. The temperature radial dependence was obtained from HELIOS’ observations for a wind speed in the range 600–700 km s$^{-1}$ (Marsch 1991).

The magnetic field power spectral density (PSD hereafter) was computed from the trace of the spectral matrix using a fast Fourier transform. Leakage effects were mitigated using a Hanning windowing and a 33 point moving average was applied to obtain the spectral estimates. PSDs relative to this alignment are shown in Figure 1(A). The red and green traces refer to MESSENGER and WIND, respectively. Both spectra show a breakpoint beyond which the spectral slope remarkably increases (see Table 1).

For the sake of simplicity and for historical reasons we will indicate this last frequency range, which in our data analysis does not go beyond 10 Hz, as “dissipation range.”

These spectral slopes were obtained through a fitting procedure. The upper and lower frequency limits of the “dissipation range” were determined by the width of the frequency range, which was best fitted by a power law. In this way, a frequency band around the spectral knee, where the spectral slope sometimes steepens gradually, and the high frequency flattening of the spectrum, which indicates that the noise level has been reached (Markovskii et al. 2008), were not included in the analysis. The adopted frequency boundaries are indicated by white circles in Figures 1 and 2.

The two frequency breaks, approximately 0.33 Hz and 0.53 Hz for WIND and MESSENGER (Table 1), were obtained from the intersection of the relative spectral fits and the associated errors from the fits uncertainties.

The second MESSENGER–WIND alignment occurred during DOY 100 of 2011 when MESSENGER was orbiting around Mercury and the angular separation was smaller than 14$^\circ$ in longitude and 5$^\circ$ in latitude from DOY 97 to DOY 106. For about 9 out of the 12 hr orbital period, MESSENGER was in the solar wind.

WIND observed a fast stream during DOY 102–104 (see Table 1). Using an average speed of 586 km s$^{-1}$, we selected the corresponding interval at MESSENGER, 41 hr before, and we checked the correspondence of the large-scale magnetic field structures observed by both spacecraft. We also made sure that the magnetic field fluctuations were not corrupted by upstream waves of Mercury’s foreshock (Le et al. 2013).

MESSENGER’s plasma parameters were estimated from those measured by WIND (Table 1). The radial index used for the proton temperature was $-0.826$ (Marsch 1991), with the wind speed being in the range 500–600 km s$^{-1}$.

Magnetic field PSDs for this alignment are shown in Figure 1(B), in the same format as panel (A). Values of the spectral indices and frequency breaks are reported in Table 1. In this case, the frequency separation is larger, which is consistent with a wider radial separation.

The third alignment occurred between WIND and ULYSSES around DOY 241 of 2007, when ULYSSES was at 1.4 AU
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The same fast stream observed by WIND during DOY 239–243 reached ULYSSES two days later (see Table 1). The spectral profiles are again similar to each other (Figure 1(C)), being characterized by a clear inertial range and a much steeper “dissipation range.” The different locations of the break confirm the radial trend observed in the previous two alignments.

We extended the radial excursion using additional observations performed by ULYSSES within fast wind at 3.2 and 5.3 AU (Table 1). These extra intervals completed our study between 0.42 and 5.3 AU.

These spectra are shown, together with all previous spectra, in a summary plot in Figure 2 and confirm that the frequency breaks (see Table 1) are shifted to lower and lower frequencies for larger and larger distances. Altogether, between 0.42 and 5.3 AU, the break experiences a frequency shift larger than one decade.

Finally, we verified that the positions of the frequency breaks reported in Table 1 were stable against a change in the length of the chosen time interval, performing the same spectral analysis within the first and second halves of each interval. In none of them did the spectral break vary by more than a factor of 1.2.

These last ULYSSES events show a shallower spectral range for the “dissipation range” which might be associated with the compressive character of the fluctuations (Alexandrova et al. 2008). However, for all the analyzed intervals we found a gradual increase of magnetic compressibility, defined as the ratio between the intensity spectrum and the trace of the spectral matrix, across the break, from values around a few percent to ~20% but we did not find striking differences able to justify the remarkable different spectral slopes recorded at 3.2 and 5.3 AU by ULYSSES.

On the other hand, while the angle between the mean field and the sampling direction (θBR in Table 1) constantly increases with heliocentric distance, there is a slight tendency toward shallower slopes that could be justified by the fact that larger values of θBR allow us to resolve fluctuations with k⊥ that are progressively larger than k∥ (Alexandrova et al. 2012; Chen et al. 2010). As a matter of fact, predictions for a critically balanced whistler or KAW cascade would suggest a decreasing slope toward −7/3 in the perpendicular direction (Schekochihin et al. 2009).

It is interesting to compare the scales associated with the frequency breaks reported in Table 1 with those corresponding to the local proton Larmor radius λL and the proton inertial length λi since each of these scales implies a different theoretical dissipation mechanism.

The quantities λL and λi have been computed in terms of wavenumber k as λL = Ωp/νth and kL = ωp/c and reported in Figure 3(A) as a function of the radial distance R. In the same Figure, we also report the values of κb = 2πfbr/νsw corresponding to the observed frequency break and the wavenumber κL corresponding to the resonance condition for parallel propagating Alfvén waves. Following Leamon et al. (1998b), in a simple slab calculation, assuming that the particle is moving at a speed equal to the thermal speed vth and that the resonant damping starts at ωp = κLvth, the minimum wavenumber resulting from the resonant condition ωr + |k|vth = Ωp is given by κr = Ωp/(vth + vth). Finally, for sake of completeness, we show also values of the wavenumber κg associated with ion gyrofrequency.

κb reveals a clear radial dependence, following a power law of the kind κb = (3.4 ± 0.2) × 10⁻³R⁻¹.⁰₉±0.⁰₈, similar to the behavior of fbr = (3.2 ± 0.2) × 10⁻¹R⁻¹.⁰₉±0.₁₁, which is not shown here.

The radial behavior of κb is very similar to that of κL = (7.0 ± 0.5) × 10⁻³R⁻¹.⁰₂±0.₁₀ and, as expected since β ~ 1 in all our cases, to that of κL = (7.0 ± 0.4) × 10⁻³R⁻¹.⁰₂±0.₁₀. Far enough from the previous ones is the behavior of the wavenumber relative to the expected proton cyclotron gyrofrequency which shows a radial dependence of the kind κg = Ωp/νsw = (6.3 ± 1.2) × 10⁻⁵R⁻¹.⁶₂±0.₃₁. The best agreement with κb is shown by κr, the wavenumber relative to the resonance condition for cyclotron damping, characterized by a power law of the kind κr = (3.5 ± 0.2) × 10⁻³R⁻¹.⁰₆±0.₁₀. κr shows a small departure only for the largest heliocentric distances. This resonant condition did not consider the cos θBR, which takes into account that k is along the direction of the local mean field while we are sampling along the radial direction at an angle θBR.

These angular estimates, reported in Table 1, were obtained on temporal windows comparable with the duration of the trailing edge of each stream.

In order to account for the effect of θBR in the hypothesis of mostly parallel propagation, we plotted in Figure 3(B) values of κL, κr, and κg versus κb/ cos(θBR) (Markovskii et al. 2008). The wavenumber κr is that which most closely follows κb/ cos(θBR). The difference with respect to κi and κL is amplified for higher values of k. These results strongly support a possible role of a cyclotron-resonant dissipation mechanism in the observed frequency shift of the spectral break (Leamon et al. 1998a).

Figure 3. Panel (A): radial behavior of κb (cyan circles, associated errors covered by the symbols), κL (green squares), κL (blue triangles), κr (red triangles), and κg (magenta diamonds). The relative best-fit curves are shown in the same corresponding colors. Panel B: κi, κL, and κr vs. κb/ cos(θBR).

(A color version of this figure is available in the online journal.)
3. DISCUSSION AND CONCLUSIONS

We investigated the radial dependence of the spectral break between the fluid and kinetic scales in the power density spectra of interplanetary magnetic field fluctuations, between 0.42 and 5.3 AU, during radial alignments between MESSENGER and WIND for the inner heliosphere and between WIND and ULYSSES for the outer heliosphere.

For the first time in the literature, we found a well-established radial dependence of the high frequency spectral break of the kind $f_b \sim R^{-1.09}$. This radial trend is much slower than that observed for the spectral break separating the $f^{-1}$ from the $f^{-5/3}$ frequency regions which is $f_b \sim R^{-1.5}$ (Bruno & Carbone 2013). This supports the fact that the turbulent character of the fast wind increases during the wind expansion since the effective Reynolds number can be estimated, while adopting the classical hydrodynamics relationship, by the square of the ratio of the scales associated with these two spectral breaks (Batchelor 1953).

The radial dependence of the wavenumber associated with the frequency break $\kappa_b \sim R^{-1.08}$ is very similar to the one shown by the wavenumbers corresponding to the proton inertial length $\lambda_i$ and the proton Larmor radius $\lambda_L$. However, the best agreement is found for the wavenumber $\kappa_r$ corresponding to the resonance condition for parallel propagating Alfvén waves. This correspondence also held when we took into account the effect of the finite angle between the local magnetic field, along which the resonant waves are propagating, and the radial direction, which corresponds to the sampling direction. These results support the suggestions of Leamon et al. (1998a), according to whom a cyclotron-resonant dissipation mechanism must participate in the spectral cascade together with other possible kinetic noncyclotron-resonant mechanisms.

The large radial extent, the selection of only fast wind, the choice to exploit radial alignments between different $s/c$, and the use of much higher data sampling make this analysis different from all the previous ones that appeared in the literature, and allowed us to demonstrate the radial dependence of the inertial range's high-frequency break.

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