# Magnetic field spectral evolution in the inner heliosphere


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(Dated: September 7, 2022)

Parker Solar Probe and Solar Orbiter data are used to investigate the radial evolution of magnetic turbulence between $0.06 \lesssim R \lesssim 1$ au. The spectrum is studied as a function of scale, normalized to the ion inertial scale $d_i$. Close to the Sun, the inertial range is limited with a power law exponent consistent with the Iroshnikov-Kraichman phenomenology of Alfvénic turbulence, $\alpha_B = -3/2$, independent of plasma parameters. The inertial range grows with distance, progressively extending to larger spatial scales, while steepening towards a Kolmogorov scaling, $\alpha_B = -5/3$. It is observed that spectra for intervals with large magnetic energy excesses and low Alfvénic content steepen significantly with distance, in contrast to highly Alfvénic intervals that retain their near-Sun scaling. The fact that slower solar wind streams tend to show steeper spectra may be attributed to the positive correlation between solar wind speed and Alfvénicity.

## I. INTRODUCTION

The solar wind flow transports a wide range of magnetic field and plasma fluctuations [1, 2]. Because fluctuations are predominantly Alfvénic (i.e., magnetic field and velocity fluctuations exhibit the correlations typical of outwardly propagating Alfvén waves) [3], and relative density fluctuations are very small solar wind turbulence is usually discussed within the phenomenologies of incompressible magnetohydrodynamic (MHD).

During the expansion, non-linear interactions result in a cascade of the energy towards smaller scales [4]. Therefore, the energy injected into the solar wind at large scales, likely of solar origin, cascades downwards until it reaches ion scales, at which point the dynamics involve kinetic processes and structures such as ion cyclotron damping, kinetic Alfvén waves, kinetic scale current sheets, etc. [5–9]. Turbulence is thought to be one of the main processes contributing to the non-adiabatic expansion, as well as the acceleration of the solar wind (SW) [4]. MHD turbulence phenomenologies predict different power law exponents depending on prevailing characteristics of the turbulence, such as spatial wave-number anisotropy [10, 11], intermittency measures, and the scale-dependent correlation between velocity and magnetic field [12, 13].

The variability of solar wind turbulence properties in the inner heliosphere reflects the diversity of solar coronal sources, that modulate the density, velocity, temperature, and ion composition of the plasma. As a result, several factors, including the role played by large-scale gradients [2]; the proximity to the heliospheric current sheet [14, 15]; the presence of magnetic field switchbacks [16–18]; large-scale velocity shear in the SW [1], strongly influence the properties of turbulence, resulting in a wide range of spectral scalings. By means of fitting the power-spectrum within a constant range in the frequency domain, recent statistical studies of PSP data, have recovered a non-evolving velocity spectral index close to $-3/2$, independent of the radial distance from the Sun [19], while the magnetic field spectrum steepens from a -3/2 slope at $\sim 0.2$ $au$ to a -5/3 slope at $\sim 0.6$ $au$ [19, 20]. Moreover, both the lower frequency spectral break between the $f^{-1}$ and $f^{-5/3}$ regimes, as well as the high-frequency break, demarcating the beginning of the kinetic scales, appear to shift to lower frequencies with increasing heliocentric distance, consistent with earlier studies [20–22].

When studying the radial evolution of turbulence in the solar wind, two scales of integral importance are the ion inertial scale $d_i = V_A/\Omega_i$, and (2) the thermal ion gyroradius, $\rho_i = V_{th,i}/\Omega_i$, where, $\Omega_i = e|B|/m_p$, is the proton gyrofrequency, $e$ is the elementary charge, $|B|$ is the magnitude of the magnetic field, and $m_p$ is the mass of the proton. With increasing heliocentric distance, both physical scales ($d_i$, $\rho_i$) increase [21, 23]. It is thus natural to expect that the relative physical scale of fluctuations of a given frequency decreases as the solar wind expands. Here we aim to understand the radial evolution of magnetic turbulence and to study the basic features of scaling laws for solar wind fluctuations in terms of properly normalized physical scales. High resolution magnetic field and particle data from Parker Solar Probe ($PSP$) [24], and Solar Orbiter ($SO$) [25] missions covering heliocentric distances 13 $R_\odot \lesssim R \lesssim 220$ $R_\odot$ are utilized. The trace power-spectrum of the magnetic field is presented as a function of wavenumber, in units of either the radially dependent ion inertial length ($d_i$), or the ion gyroradius, and the evolution of the inertial range spectral index with heliocentric distance is examined.

It is shown that closer to the Sun the magnetic field power-spectrum exhibits a poorly developed inertial range that is characterized by a $-3/2$ spectral index. The inertial range extends to larger and larger scales as the solar wind expands into the interplanetary medium, with the inertial range spectral index steepening towards a $-5/3$ value. It is shown here, for the first time that the rate at which the steepening occurs is strongly depen-

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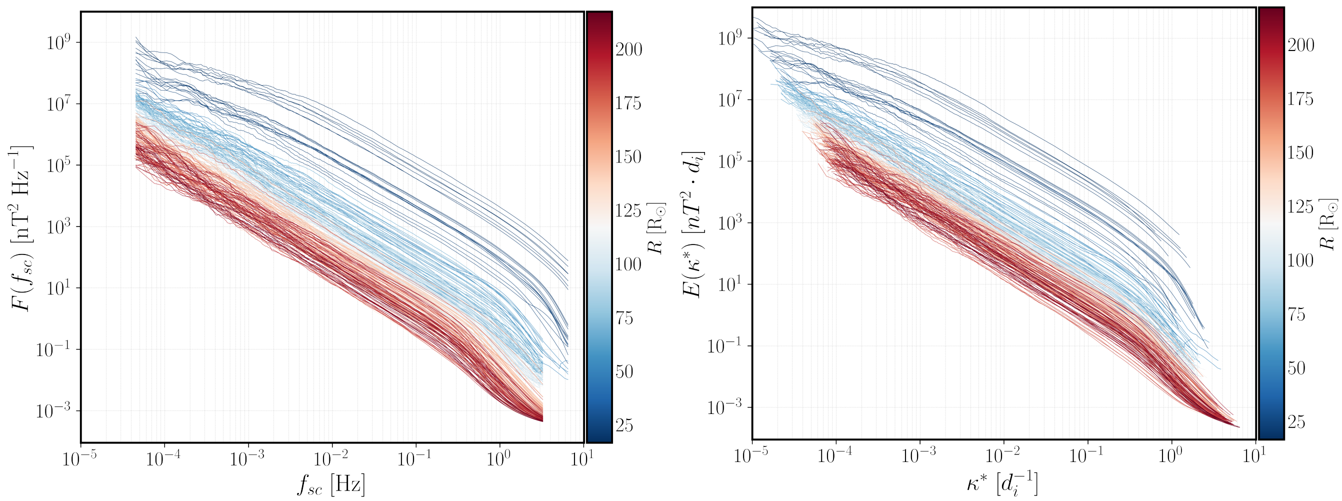


FIG. 1. Magnetic field power-spectrum, $PSD$ at different heliocentric distances. The power-spectrum is shown, as a function of (a) spacecraft frequency; (b) wavenumber $k^* = \ell^{-1}$ in units of $d_i$;

dent on magnetic energy excess and Alfvénicity of the fluctuations.

## II. DATA SELECTION AND PROCESSING

We analyzed magnetic field data from the Flux Gate Magnetometer (FGM) [26], as well as plasma moment data from the Solar Probe Cup (SPC) and Solar Probe Analyzer (SPAN) part of the Solar Wind Electron, Alpha and Proton (SWEAP) suite between January 1, 2018, and June 15, 2022, encompassing the first twelve perihelia (E1-E12) of the PSP mission. SPC data have been utilized for E1-E8, while SPAN data for E9-E12. Electron number density data derived from the Quasi-thermal noise of the FIELDS instrument [27], have been preferred over SPAN or SPC data when available. Additionally, magnetic field and particle moment measurements from the Magnetometer (MAG) instrument [28], prioritizing burst data when available, and the Proton and Alpha Particle Sensor (SWA-PAS) [29] onboard the SO mission between June 1, 2018, to March 1, 2022, were considered.

Following consideration of quality flags, time intervals that were found to be missing $\geq 1\%$ and/or $\geq 10\%$, in the magnetic field and particle timeseries have been omitted from further analysis. The remaining intervals have been resampled linearly to the highest cadence possible, based on their initial resolution. Finally, in order to eliminate spurious spikes, a Hampel filter [30] was applied to the plasma time series.

Converting the spacecraft-frame frequency derived PSD, $F(f_{sc})$ to a wavenumber PSD, $E(\kappa)$, far from the sun is possible by means of Taylor's hypothesis (TH) [31], $\kappa = 2\pi f_{sc}/V_{SW}$, that becomes questionable when both the Alfvén and spacecraft velocity are comparable to the velocity of the solar wind. Therefore, a modified version of Taylor's hypothesis that accounts for both wave propagation and spacecraft velocity is adopted [32]: in the above expression for $\kappa$ $V_{sw}$ is replaced by $V_{tot} = |\boldsymbol{V}_{sw} + \boldsymbol{V}_a - \boldsymbol{V}_{sc}|$ where $\boldsymbol{V}_{sc}$ is the spacecraft velocity, where turbulence is assumed to be dominated by outwardly propagating Alfvén waves. Note that the TH remained either moderately or highly valid for the majority of time intervals examined. with only $\sim 1.53\%$ of the intervals under study exhibiting $M_A < 1.5$, including a number sub-Alfvénic intervals during PSP $E_8 - E_{12}$ ($\sim 0.45\%$ of the entire dataset).

## III. RADIAL EVOLUTION OF MAGNETIC FIELD SPECTRAL INDEX

The radial evolution of magnetic field fluctuations in the inner heliosphere is examined using a dataset of combined PSP and SO observations. Overlapping intervals with a duration of 24 hours are considered, with the beginnings of each adjacent interval being 8 hours apart. For each interval, the trace power spectral density $F(f_{sc})$ was calculated by Fourier transform and smoothed by averaging over a sliding window of a factor of 2. The resulting spectra as a function of spacecraft frequency are presented in Figure 1a. Note that each of the curves shown is the result of averaging 5 nearby spectra that fall within the same heliocentric distance bin. Due to the expansion of the solar wind but also in par because of the turbulent cascade, a decrease of $\sim 4$ orders of magnitude in magnetic power is observed with increasing heliocentric distance. The frequency spectrum $F(f_{sc})$, was subsequently transformed into a wavenumber spectrum expressed in physical units $E(\kappa^*)$ by virtue of the modified TH:

$$E(\kappa^*) = \frac{V_{tot}}{2\pi \cdot \xi} F(f_{sc}) \; [nT^2 \cdot \xi], \tag{1}$$

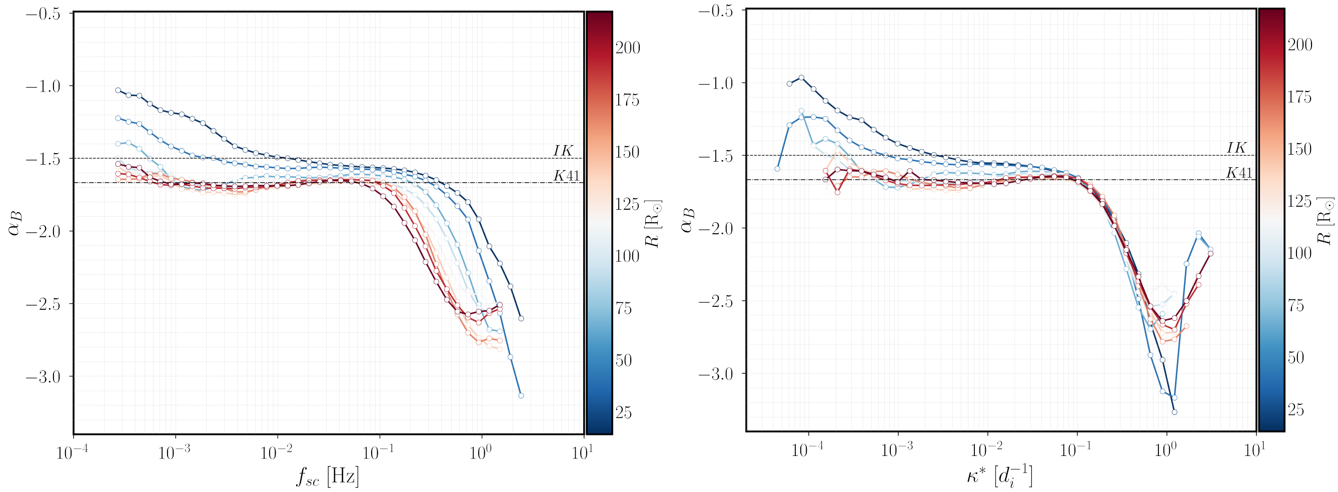


FIG. 2. Evolution of magnetic field spectral index ($\alpha_B$) as a function of distance, & (a) frequency in units of $Hz$ (b) normalized wavenumber $\kappa^*$ in units of $d_i$.

where $\kappa^* = \kappa \cdot \xi = \frac{2\pi f_{sc}}{V_{tot}} \cdot \xi$, and, $\xi = d_i, \rho_{ci}$. In Fig. 1b, the magnetic field power spectral density $E(\kappa^*)$ normalized by $d_i$,is presented as a function of heliocentric distance. The spectral index, $\alpha_B$ is obtained by taking a sliding window of one decade in the spacecraft-frame frequency (wavenumber) domain, over the smoothed spectra and calculating the best-fit linear gradient in log-log space over this window. For clarity, ten radial bins have been used, and the median value of the spectral index as a function of frequency has been estimated for intervals that fall within the same bin. The color of the curve is keyed to the mean value of the distance $R$ corresponding to the intervals within each bin. The results of this analysis are presented in Figure 2a. In the inertial range, an energy cascade rate that is independent of scale is expected, reflecting on the power-spectrum in the form of a constant spectral index over this range of scales. In light of this, it can be seen that close to the Sun (dark blue line in Figure 2a), the inertial range is limited into a narrow range of frequencies ($2\times10^{-2} - 2\times10^{-1}$Hz). As the solar wind expands in the interplanetary medium (1) a universal steepening (i.e., across all frequencies) is observed for the spectral index, $\alpha_B$, at a constant $f_{sc}$; (2) The curves shift horizontally to lower and lower frequencies. As illustrated in Figure 2a, the frequency range over which the spectral index is constant is migrating to the left while steepening with increasing distance, from $\alpha_B \approx -3/2$ to $\alpha_B \approx -5/3$. Similar behavior is observed at the largest scales. Closer to the Sun for $f_{sc} \leq 2 \times 10^{-2}$ Hz, the spectrum gets progressively shallower at lower frequencies and obtains a value of $\alpha_B \approx -1$ at $f_{SC} = 3 \times 10^{-4}$ Hz. As heliocentric distance increases, this low-frequency part of the spectrum gradually steepens, with all the frequencies approaching a $-5/3$ scaling. Therefore, as the solar wind propagates outward, the inertial range of the spectrum develops gradually, extending from higher frequencies to progressively lower and lower frequencies. Additionally, in accordance with [21] the ion scale break, separating the inertial from the kinetic range is observed to migrate to lower frequencies with distance.

To cast the results in terms of relevant physical scales, we considered the evolution of $\alpha_B$ into the wavenumber domain normalizing by either the ion inertial length ($d_i$) or the ion gyroradius ($\rho_i$). The evolution of the spectral index as a function of distance ($R$) in the wavenumber domain normalized by $d_i$, is illustrated in Figure 2b. It is readily seen, that the vertical shifting of the curves to lower frequencies, observed in Figure 2a, has vanished: all the curves roll over at $kdi \approx$ 0.1 and overlap at smaller scales. At the largest scales $\kappa^* \lesssim 8 \times 10^{-2}$, the normalization does not seem to considerably affect the radial development of the spectral index as a steepening that closely resembles Figure 1a is recovered. On the other hand, as shown in Figure 1b, the small scale break, demarcating the beginning of the transition region, $\kappa^* \approx 9\times10^{-2}$ ($\rho_i^{-1}$), does not show any remarkable evolution with distance and stays constant in physical space. We do not show plots using $\rho_i$ as normalization because the spectra do not collapse as clearly into one curve at small scales, demonstrating that $d_i$ is the more appropriate scale for such a normalization.

### A. Dependence of $\alpha_B$ on plasma parameters

To disentangle the spectral variation with distance from changes due to the differing plasma parameters of different solar wind streams the dependence of $\alpha_B$ on the normalized cross helicity $\sigma_c$

$$\sigma_c = \frac{E_o - E_i}{E_o + E_i}, \tag{2}$$

a measure of the relative amplitudes of inwardly and outwardly propagating Alfvén waves, and the normalized

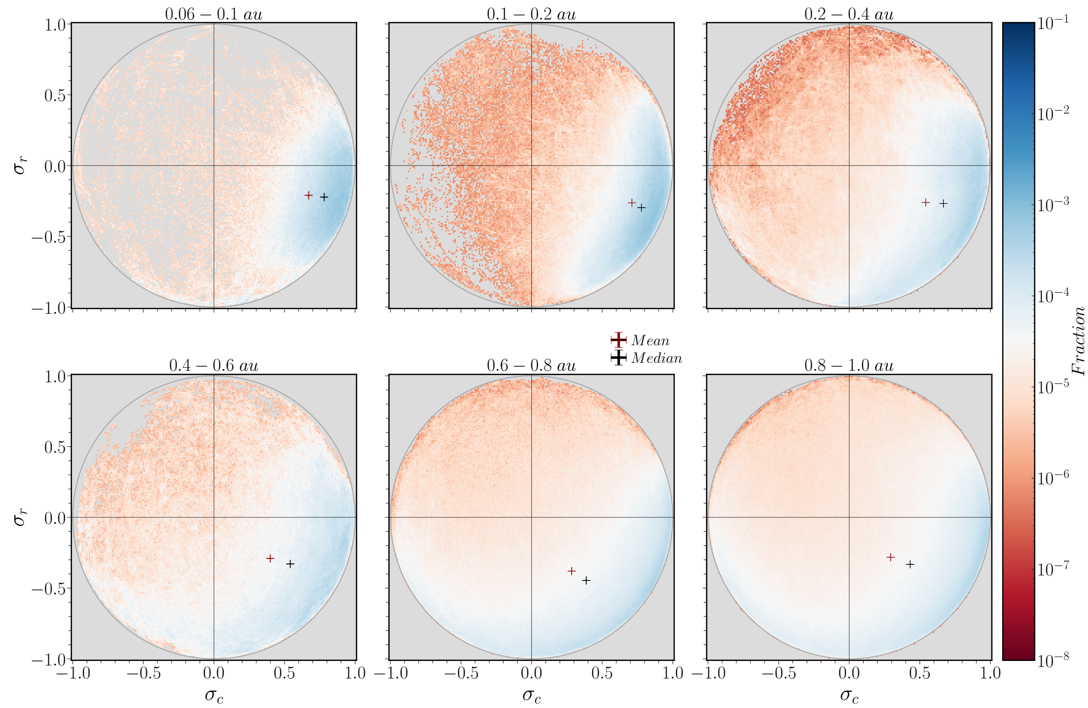


FIG. 3. The joint distribution of normalized cross-helicity $\sigma_c$ and normalized residual energy $\sigma_r$ at different heliocentric distances.

residual energy $\sigma_r$

$$\sigma_r = \frac{E_V - E_b}{E_V + E_b}, \tag{3}$$

indicating the balance between kinetic and magnetic energy is examined. $E_q = \frac{1}{2}\langle \delta \boldsymbol{q}^2 \rangle$ denotes the energy associated with the fluctuations of the field $\boldsymbol{q}$. In particular, $E_{o,\ i}$ can be estimated using Elsasser variables, defining outward and inward propagating Alfvénic fluctuations [33, 34]

$$\delta \boldsymbol{Z}_{o,i} = \delta \boldsymbol{V} \mp sign(B_0^R)\delta \boldsymbol{b}, \tag{4}$$

$\delta \boldsymbol{B} = \boldsymbol{B} - \boldsymbol{B_0}$, $\boldsymbol{B_0}$ the background magnetic field, $\delta \boldsymbol{b} = \delta \boldsymbol{B}/\sqrt{\mu_0 m_p n_p}$ the magnetic fluctuations in Alfvén units and $B_0^r$ the ensemble average of $B_R$, utilized to determine the polarity of the radial magnetic field [19]. We have also considered the variation of $\alpha_B$ with solar wind speed $V_{sw}$, the ratio of magnetic to thermal pressure, $\beta \equiv n_p K_B T/(B^2/2\mu_0) \ll 1$, and the field/flow angle $\Theta_{BV}$ was also examined. Though we do not focus on $\beta$, and $\Theta_{BV}$ here, we will comment on this in Section IV. The evolution of $\alpha_B$ is investigated by fitting the magnetic spectrum over a constant range $(10^{-3} - 5 \times 10^{-2}\ d_i^{-1})$. The spatial scales covered in this range are large enough to avoid instrumental noise but at the same time small enough not to encroach on the outer scale of turbulence. Moreover, this scale range falls well within the inertial range to the extent that it is developed and large enough to enable reliable spectral indices to be obtained. To mitigate the effects of mixing different types of solar wind, and to ensure that the plasma parameters under study do not vary significantly within the interval the duration of individual intervals has been reduced to $d = 1$ hr. However, by reducing the interval size to 1 hr, the observed spectra at a given heliocentric distance are slightly steeper than those obtained using the longer duration intervals presented in Section III.

### B. Solar Wind Speed, $V_{SW}$

Intervals associated with the fast solar wind $V_{SW} \gtrsim 600\ km\ s^{-1}$ comprise only a minor fraction of our dataset. There are, however, a number of intervals with $V_{SW}$ in the range $200\ km\ s^{-1} \lesssim V_{SW} \lesssim 600 km\ s^{-1}$ sampled by PSP and SO throughout the inner heliosphere that can provide insight into spectral properties as a function of wind speed, $V_{SW}$ or better advection time $\tau_{adv} = R/V_{SW}$. As shown in Figure 4a, close to the Sun, inside 30 $R_s$, no significant differences in spectral index with solar wind speed are found, with an inertial range scaling close to the IK prediction. However, the dependence on solar wind speed at a given heliocentric distance becomes increasingly apparent as the solar wind expands: while steepening occurs regardless of solar wind speed, the steepening process is more efficient for the slower component of the solar wind. As a result, at $R \approx 1$ au, the dependence of the spectral index on speed is clear, with the spectral index being consistent with a K41 scaling in the fast wind and a steeper scaling of $\approx -1.8$ for

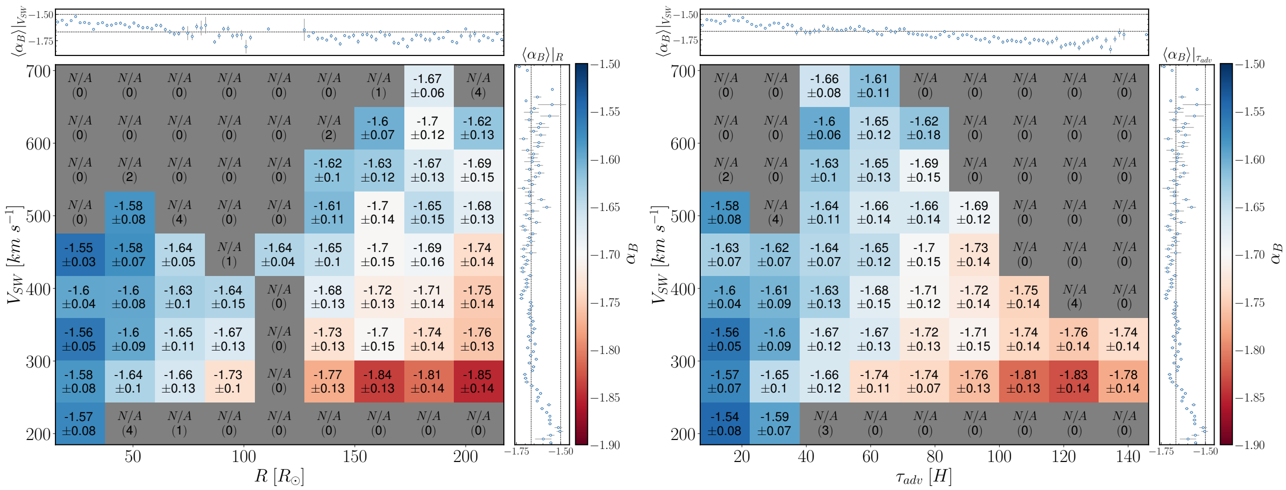


FIG. 4. Magnetic field spectral index $a_B$ as a function of (a) heliocentric distance; (b) advection time of the solar wind, $\tau_{adv}$, and solar wind speed.

the slowest winds. Categorizing the spectral index as a function of $\tau_{adv}$, Figure 4b, instead of radial distance one finds that for $\tau_{adv} < 60Hrs$ no clear trend is observed for the spectral index as a function of wind speed. Beyond, this point, though steepening is monotonic with $\tau_{adv}$ at all wind speeds. Overall, a mild dependence of the inertial range spectral index, $\alpha_B$, is observed with solar wind speed with slower speed intervals exhibiting steeper spectra on average. Lower speed intervals display a significant radial steepening as compared to faster winds that only display a slight steepening. However, the lack of spectral index dependence on wind speed closer to the Sun suggests that the spectra are initially similar regardless of speed.

### C. Normalized Cross Helicity, $\sigma_c$, & Normalized Residual Energy $\sigma_r$

The joint $\sigma_c$ - $\sigma_r$ distribution, estimated using 1 minute-long moving average of the respective timeseries is presented in Figure 3. The median and mean value of $\sigma_c$ and $\sigma_r$ for each heliocentric distance bin are also shown as red and black crosses respectively. The gray circle defines fluctuations with perfect alignment between velocity and magnetic field, given by $\sigma_c^2 + \sigma_r^2 = 1$. Closer to the sun (0.06-0.1 au) turbulence is highly Alfvénic, dominated by outwardly propagating waves ($\sigma_c \approx 0.85$), and in slight excess of magnetic energy ($\sigma_r \approx -0.15$). A small population of strongly magnetically dominated intervals characterised by very low alfvénic content (i.e., $\sigma_r \approx -1$, and $\sigma_c \approx 0$, mostly associated with heliospheric current sheet (HCS) crossings is also observed (see [15]). At larger heliocentric distances the mean/median value of $\sigma_c$ progressively decreases [19, 20]. Several mechanisms have been proposed to explain the diminishing dominance of outwardly propagating waves with increasing heliocentric distance due to wave reflection, including velocity shears [35] and the parametric decay instability [36, 37]. At 1au, $\sigma_r$ is clearly more negative than in the near-Sun environment, but it does not show a clear trend with radial distance. In the distance range of 0.6-1 au, most of the data points are concentrated in the lower half, with a few intervals having slightly positive $\sigma_r$ values. In addition, datapoints located in the bottom left quadrant are increasing with distance, indicating a radially decreasing dominance of waves propagating outward

Subsequently, the power-spectra of the fluctuating fields $\delta \boldsymbol{b}, \delta \boldsymbol{V}, \delta \boldsymbol{Z}_{o,i}$ have been obtained by means of Fourier transform and both $\sigma_c$, and $\sigma_r$ have been estimated by integrating the resulting spectra over a constant range ($10^{-3} - 5 \times 10^{-2}\ d_i^{-1}$ ) in the wavenumber domain normalized by the ion inertial length. The dependence of the spectral index on $|\sigma_c|$ and $\sigma_r$ as well as the radial distance (R) is presented in Figure 5a,b for $\sigma_c$ and $\sigma_r$ respectively. These show how highly alfvénic ($|\sigma_c| \approx 1$) and energetically equipartitioned intervals display little spectral evolution, while evolution to significantly steeper spectra is associated with low $|\sigma_c|$ and/or large magnetic energy excess, with the data at large distances consistent with 1 AU results [38–40].

## IV. CONCLUSIONS

Using high-resolution data from the inner heliosphere, extending from the Alfven region to 1 AU, we have analyzed 1) how the statistical signatures of turbulence evolve with heliocentric distance and (2) the plasma parameters driving the evolution.

We show that the most relevant plasma scale for the normalization of magnetic field energy spectra is the ion inertial length ($d_i$) and that closer to the Sun, the inertial range of the magnetic field power-spectrum is poorly developed i.e., the range of scales over which $\alpha_B$ re-

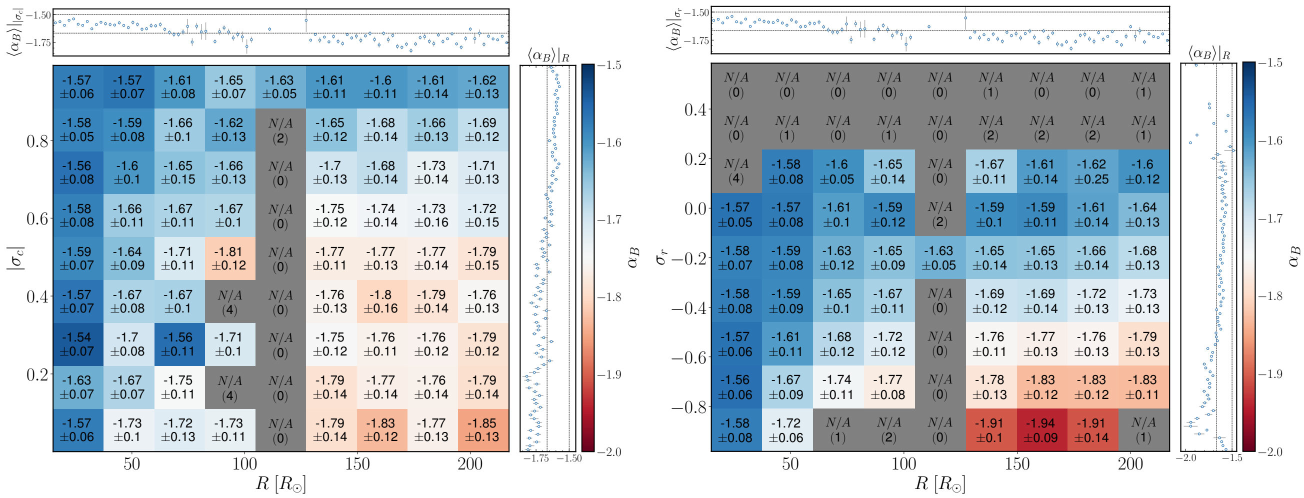


FIG. 5. (a) Magnetic field spectral index $\alpha_B$ as a function of heliocentric distance and normalized cross helicity $\sigma_c$. (b) Magnetic field spectral index $\alpha_B$ as a function of heliocentric distance and normalized residual energy $\sigma_r$.Error values indicate the standard error of the mean.

mains constants is limited; its value is closer to that found in the IK phenomenology of alfvénic turbulence i.e., $\alpha_B = -3/2$. As the solar wind expands into the interplanetary medium, the inertial range extends to progressively larger scales, while at the same time the inertial range spectral index steepens to a Kolmogorov-like value, $\alpha_B = -5/3$.

We demonstrate that the rate at which $\alpha_B$ steepens is strongly dependent on the normalized residual energy and normalized cross helicity of the intervals under study. In particular, intervals with high alfvénic content ($|\sigma_c| \approx 1$), and equipartitioned in $E_V$-$E_b$ ($\sigma_r \approx 0$) seem to retain their near-Sun scaling, and show a minor steepening with radial distance. In contrast, magnetically dominated and balanced intervals are observed to strongly steepen, resulting in anomalously steep inertial range slopes at 1 au, consistent with previous studies [38–40].

While $|\sigma_c| \approx 1$ and $\sigma_r \approx 0$ values may be found in slow wind streams, especially closer to the sun, they are statistically less relevant than in fast winds [19]. As a result, the steeper spectral indices observed in the slow solar wind can be explained by the positive correlation between solar wind speed and $\sigma_c$, $\sigma_r$.

Intervals with large magnetic energy excess closer to the Sun do not display the steep spectra observed at 1 au, an observation attributed by [40] to the correlation between magnetic coherent structures and highly negative $\sigma_r$ values [41]. Recent studies [23, 42], suggest that magnetic field intermittency is strengthened with increasing heliocentric distance in the inner heliosphere, but no similar analysis has been conducted for the velocity field. However, it has been well documented that velocity spectra do not display radial evolution [19] and exhibit a scaling of $a_v = -3/2$ at 1 au [39]. Based on our results, we expect that both the magnetic and velocity field spectra display a $-3/2$ scaling closer to the Sun, with the evolution of the magnetic spectrum related to the in-situ generation of magnetic coherent structures during expansion. A study of the evolution of $\alpha_B$ and $a_v$ as a function of radial distance as well as intermittency is ongoing (Makris et al., in preparation).

Turbulence in the solar wind is anisotropic with respect to the mean magnetic field [see, e.g., reviews by 43–45, and references therein]. Horbury *et al.* [46], Wicks *et al.* [47], Kiyani *et al.* [48] have shown that when the field/flow angle $\Theta_{BV}$ is $\Theta_{BV} = 90°$, then the inertial range range scales like either $\alpha_B \approx =5/3$, or sometimes $\approx =3/2$, consistent with a critical balance cascade and dynamical alignment models respectively. In the parallel direction, $\Theta_{BV} = 0°$, it is nearer $\alpha_B \approx -2$. In contrast, when a global magnetic field is utilized to estimate $\theta_{BV}$, no anisotropy in the spectral index as a function of $\Theta_{BV}$ is observed [49, 50]. Though not shown here, we find that for a fixed heliocentric distance, there is no correlation between $\Theta_{BV}$ and $\alpha_B$ when using a global magnetic field. Note that a similar result was obtained when considering the dependence of $\alpha_B$ on plasma $\beta$, suggesting that these two parameters are not related to the steepening of the spectrum. To further clarify the debate between a local, scale-dependent and global background magnetic field analysis of the spectral index evolution as a function of radial distance and $\Theta_{BV}$ using the Undecimated Discrete Wavelet Transform method [48] is ongoing (Liodis & Sioulas et al., in preparation).

Our findings will help us gain a better understanding of how solar wind turbulence is generated and transported and will guide future models of solar wind turbulence.

**ACKNOWLEDGMENTS**

This research was funded in part by the FIELDS experiment on the Parker Solar Probe spacecraft, designed and developed under NASA contract NNN06AA01C; the NASA Parker Solar Probe Observatory Scientist grant NNX15AF34G and the HERMES DRIVE NASA Science Center grant No. 80NSSC20K0604. The instruments of PSP were designed and developed under NASA contract NNN06AA01C.

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