

Reply to “Comment from Anonymous Referee #1”

We appreciate the referee’s comments on our manuscript entitled “Effect of Intermittent Structures on the Spectral Index of Magnetic field in the Slow Solar Wind” [angeo-2022-28]. We have taken the referee’s suggestions fully into account. In our response, each of the referee’s suggestions is followed by the corresponding reply and revision marked in bold. Line numbers refer to the original submission. The comments have helped us to improve our manuscript and clarify the contents significantly. We are grateful for the referee’s suggestions.

The manuscript “Effect of Intermittent Structures on the Spectral Index of Magnetic field in the Slow Solar Wind” by X. Wang and co-authors deals with the investigation of the intermittent properties of solar wind magnetic field fluctuations as measured by the spectral slope of their power spectral density. The paper is well written and the topic is within the scope of ANGEOS. However, there are some missing aspects that need to be properly framed out and considered before it can be accepted for publication.

Major comments

1. The paper accounts for finding a relationship between the spectral exponent and the level of intermittency in slow solar wind streams observed at 1 AU by WIND. The results shown in the paper are not new since a close correspondence between intermittency and changes in the 2nd-order scaling properties has been well established. The main novelty is only the observed analytical relation (fit). I would suggest the authors to carefully revise the manuscript to clearly state this. There is a huge literature on the correction of the scaling properties due to intermittency as well as many improved cascade models have been proposed to revise the original Kolmogorov results.

Reply: Thanks for the suggestion! We agree that the main novelty of this work is the observed analytical relation (fit). According to the suggestion, we revise the abstract and the main text to clearly state this point as follows.

In “Abstract”, we revise two sentences as “... However, an analytical relationship between intermittency level and the magnetic spectral index has not been shown yet. ... Accordingly, an empirical relation is established between α_B and I_{max} for the first time as $\alpha_B = 0.4 \exp(-I_{max}/5) - 2.02$...”

In the main text, we add the following sentences at Line 59: “From the previous studies mentioned above, people have realized that ... a close correspondence between intermittency and changes in the 2nd-order scaling properties has been well established. There is a huge literature on the correction of the scaling properties due to intermittency, and many improved cascade models have been proposed to revise the original Kolmogorov results. However, no analytical relationship between the magnetic spectral index and the level of intermittency

has been shown so far. The main novelty of this work is that we show for the first time the analytical relationship between the magnetic spectral index and the level of intermittency by performing a fit on the observational results.”

In “Conclusions”, we replace the first sentence at Line 294 by the new one: “In this paper, we present for the first time the analytical relation between the magnetic spectral index α_B in the inertial range and the level of intermittency I_{max} at the time scale of $\tau = 24$ s in the slow solar wind.”

2. The authors claim, indeed, that the steeping of the spectrum is closely connected with intermittency. However, this could be only partially true since different spectral slopes are observed if looking along different directions with respect to the mean field. As the authors say there is a huge literature on the anisotropy of spectral slopes but they introduce a measure of the level of intermittency based on the trace of the PVI (so, something isotropic) and then also evaluate spectral slopes for the trace of the magnetic field fluctuations. Thus, my question is: how the presented results could be biased by anisotropy of magnetic field fluctuations? A possible check could be performed by looking at the dependence of the spectral slope across different directions as a function of the threshold crossing of the PVI along the different directions again. Would the results be robust or is there any dependence on the predominance of fluctuations along a specific direction?

In other words, what is the difference between an interval with $|PVI_j| > 2$ but $|PVI_k| < 2$ and an interval with $|PVI_j| > 2$ for all $j = x, y, z$?

Reply: Thanks for the suggestion! We agree that it is necessary to check whether the presented results will be biased by the anisotropy of magnetic field fluctuations or not. According to the suggestion, we add a subsection “4.2 Influence of anisotropy of magnetic field fluctuations” in “4. Discussion”. In this subsection, we perform a check to see if the spectral index is dependent on the predominance of fluctuations along a specific direction. Here the direction of the predominant fluctuations is indicated by maximum variance (L) direction, which is obtained from the Minimum Variance Analysis. We show in Figure 9 the variations of the magnetic spectral index as a function of the angle between L and i direction (θ_{Li}) (where i denotes the x -axis, y -axis, and z -axis of geocentric solar ecliptic coordinates), along with the variations of the spectral index versus the angle between L and the mean magnetic field direction of each interval (θ_{LB}). It is found that the influence of the anisotropy of predominant fluctuations on the spectral index is not as significant as the influence of the level of intermittency (I_{max}) on the spectral index. Therefore, our results are robust. In subsection 4.2 of the new version of the manuscript, we describe this point in detail:

4.2 Influence of anisotropy of magnetic field fluctuations

Since different spectral indices are observed if looking along different directions

with respect to the mean field as mentioned in the introduction, it is necessary to reveal how the presented results shown in Figure 6 could be biased by the anisotropy of magnetic field fluctuations. We then perform a check to see if the spectral slope is dependent on the predominance of fluctuations along a specific direction. Here the direction of the predominant fluctuations is indicated by the maximum variance (L) direction, which is obtained from the Minimum Variance Analysis (Sonnerup and Cahill, 1967). We show in Figure 9 the variations of the magnetic spectral index as a function of the angle between L and i direction (θ_{Li}) (where i denotes the x -axis, y -axis, and z -axis of geocentric solar ecliptic coordinates), along with the variations of the spectral index versus the angle between L and the mean magnetic field direction of each interval (θ_{LB}).

Panel(a2) of Figure 9 shows the variation of the magnetic spectral index α_B as a function of θ_{LX} . The angle $\theta_{LX} \sim 0^\circ$ means that the predominant fluctuations of the intermittent structure mainly focus on the x direction, while $\theta_{LX} \sim 90^\circ$ means that they focus on the plane perpendicular to the x direction. Only 79% of the selected intervals with $\lambda_1/\lambda_2 > 3$ are remained for the analysis, where λ_1 and λ_2 are the eigenvalues corresponding to the maximum variance direction and the intermediate variance direction, respectively. This condition guarantees that the maximum variation direction is determined precisely, and the fluctuations in the L direction are distinctly dominant in each interval. Panels (a1) and (a2) are plotted in the similar format as Figure 6. For a given pixel in panel (a2), the color denotes the number of cases normalized by the maximum number among the corresponding θ_{LX} bin, and the maximum number of each bin is shown in panel (a1). The gray solid circles represent the average α_B in each θ_{LX} bin. The dotted gray lines represent the upper/lower quartiles. The gray solid circles show that there is a slight decreasing trend for the average spectral index α_B (from -1.76 to -1.86) as θ_{LX} increase from 0° to 90° . However, if we consider the quartiles (i.e., from $-1.76^{+0.14}_{-0.10}$ to $-1.86^{+0.13}_{-0.14}$), the slight trend is nearly negligible. Therefore, the magnetic spectral indices of the intervals with the predominant fluctuations parallel or perpendicular to the x direction are not significantly different.

Figure 9bcd show the variation of the magnetic spectral index as a function of θ_{LY} , θ_{LZ} , and θ_{LB} . A slight increasing trend (from $-1.89^{+0.17}_{-0.17}$ to $-1.84^{+0.14}_{-0.13}$) appears in panel (b2), but the trend is not significant, neither, considering the errors. In panel (c2), the average α_B (gray solid circles) nearly keeps constant at -1.85 . In panel (d2), the average α_B (gray solid circles) varies with θ_{LB} , and no clear trend exists.

According to the results presented in the panels of Figure 9, we suggest that the influence of the anisotropy of predominant fluctuations on the magnetic spectral index is not as significant as the influence of the intermittency level I_{max} on the index (when I_{max} increases from 0 to 20, α_B decreases from -1.63 to -2.01).

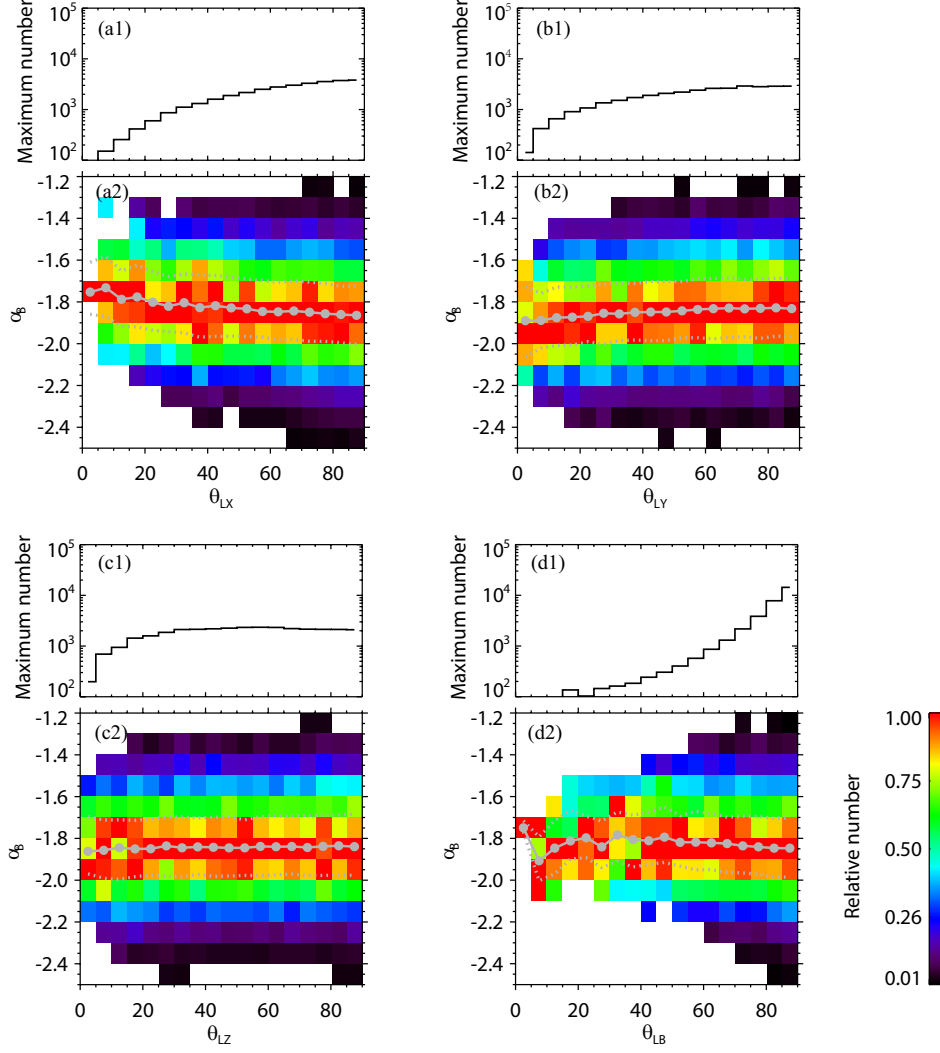


Figure 9: (a2) Joint distribution of θ_{LX} and magnetic spectral index α_B for the 33,261 intervals with $\lambda_1/\lambda_2 > 3$. For a given pixel, the color denotes relative number, which is the number of the cases normalized by the maximum number among the corresponding θ_{LX} bin. The maximum number of each bin is shown in panel (a1). The pixels containing no more than 10 cases are ignored. The gray solid circles represent average α_B in each θ_{LX} bin. The dotted gray lines represent the upper/lower quartiles. Panels (b1)(b2) are plotted in the same format as panels (a1)(a2) but for θ_{LY} . Panels (c1)(c2) correspond to θ_{LZ} . Panels (d1)(d2) correspond to θ_{LB} .

3. Another important point is that by only looking at the 2nd-order exponent could not be sufficient to fully characterize the intermittency. Indeed, as shown in literature (the authors, for example, mentioned the work by Veltri and Mangeney, 1999), intermittency is strictly related to multifractality that can only be measured by looking at the high-order scaling properties. It would be interesting to compare the intermittency magnitude with some multifractal indicators of intermittency as the multifractal width or the amplitude of the singularity spectrum (some parameters have been introduced in literature, see papers by Macek, Wawrzaszek).

Reply: Thanks for the suggestion! According to the suggestion, we calculate the multifractal width for the selected intervals, and compare it with the intermittency level I_{max} . We find that they are positively correlated. When $I_{max} < 3$, the multifractal width $\Delta\alpha$ rapidly increases from 0.8 to 1.05. When $I_{max} > 3$, $\Delta\alpha$ increases slowly from 1.05 to ~ 1.2 . Accordingly, we suggest that, to some extent, the multifractal width $\Delta\alpha$ and the level of intermittency I_{max} coincide with each other. In order to clarify this point in detail, we add a new subsection 4.3 as following:

4.3 Coincidence between intermittency level and multifractal width

As shown in literature (e.g., Frisch (1995); Veltri and Mangeney (1999); Salem et al. (2009)), intermittency is strictly related to multifractality that is measured by looking at the high-order scaling properties. Therefore, it is necessary to check if I_{max} used here is consistent with multifractal indicators of intermittency, such as the multifractal width introduced in a series of work by Macek, Wawrzaszek et al.

The multifractal properties can be described by the multifractal singularity spectrum of the observed time sequence. The width of the spectrum represents the extent of multifractality. Here we estimate the multifractal singularity spectrum of the magnetic field fluctuations by using the classical approach following previous studies (Paladin and Vulpiani, 1987; Macek et al., 2005; Macek and Wawrzaszek, 2009; Macek et al., 2012; Marsch et al., 1996; Burlaga, 1991; Burlaga et al., 2006; Sorriso-Valvo et al., 2017). For each selected interval, we perform the multifractal analysis on the time sequence of the magnetic field fluctuations in the maximum variance direction ($B_L(t)$) with high time resolution of $\Delta t_H = 1/11$ s. The increment of $B_L(t)$ is $\Delta B_L(t) = |B_L(t+dt) - B_L(t)|$, where $dt = 10s$ belongs to the inertial range. The time series $\Delta B_L(i)$ ($i = 1, 2, \dots, N$, with $N = T/\Delta t_H$ and T being the duration of each interval) is divided into subsets of variable scale Δs , with $j = 1, 2, \dots, M$ ($M = T/\Delta s$). A logarithmically spaced range of eight time scales $10/11$ s $< \Delta s < 150$ s is used. For each subset, the generalized

probability measure is defined as

$$\mu_j(\Delta s) = \frac{\sum_{i=(j-1)\Delta s+1}^{j\Delta s} |\Delta B_L(i)|}{\sum_{i=1, N} |\Delta B_L(i)|}. \quad (1)$$

For a given q , we calculate the q -order total probability measure, and it scales as

$$\chi_q(\Delta s) = \sum_{j=1}^M \Delta s |\mu_j(\Delta s)|^q \propto (\Delta s)^{\tau_q}, \quad (2)$$

where $q \in [-5, 5]$ with a step $dq = 1/3$ (similar to Sorriso-Valvo et al. (2017)). The scaling exponents τ_q is obtained by performing a linear fit on the log-log plot of $\chi_q(\Delta s)$ versus Δs in the inertial range $[8s, 100s]$. We then obtain the singularity spectrum from $f(\alpha) = q\alpha_q - \tau_q$ and $\alpha_q = d\tau_q/dq$ (Halsey et al., 1986). The left panel of Figure 10 presents the variations of $f(\alpha)$ versus α , with red for the intermittent interval shown in Figure 4 ($I_{max} = 13.09$), black for the intermittent interval shown in Figure 2 ($I_{max} = 4.10$), and blue for the quiet interval shown in Figure 5 ($I_{max} = 1.44$). The dots and solid lines denote the observational results and cubic polynomial fitting to them, respectively.

A quantitative description of the degree of multifractality is the width of the singularity spectrum $\Delta\alpha = \alpha_{max} - \alpha_{min}$. We estimate α_{min} and α_{max} by fitting the observed values of $(\alpha, f(\alpha))$ with the cubic polynomial and extrapolating to $f(\alpha) = 0$ as shown in the left panel of Figure 10. We find that the multifractal widths of the two intermittent intervals ($\Delta\alpha = 1.19$ in red and $\Delta\alpha = 1.16$ in black) are both much larger than that of the quiet interval ($\Delta\alpha = 0.81$ in blue). Moreover, the intermittent interval with higher level of intermittency ($I_{max} = 13.09$) also corresponds to wider singularity spectrum $\Delta\alpha = 1.19$ in red, comparing to the black one ($I_{max} = 4.10$ and $\Delta\alpha = 1.16$).

In the right panel of Figure 10, we show the statistical results of the multifractal width $\Delta\alpha$ versus the level of intermittency I_{max} for the 33,261 intervals with $\lambda_1/\lambda_2 > 3$ as mentioned in subsection 4.2. They are found to be positively correlated. When $I_{max} < 3$, the multifractal width $\Delta\alpha$ rapidly increases from 0.8 to 1.05. When $I_{max} > 3$, $\Delta\alpha$ increases slowly from 1.05 to ~ 1.2 . Accordingly, we suggest that, to some extent, the multifractal width $\Delta\alpha$ and the level of intermittency I_{max} coincide with each other.

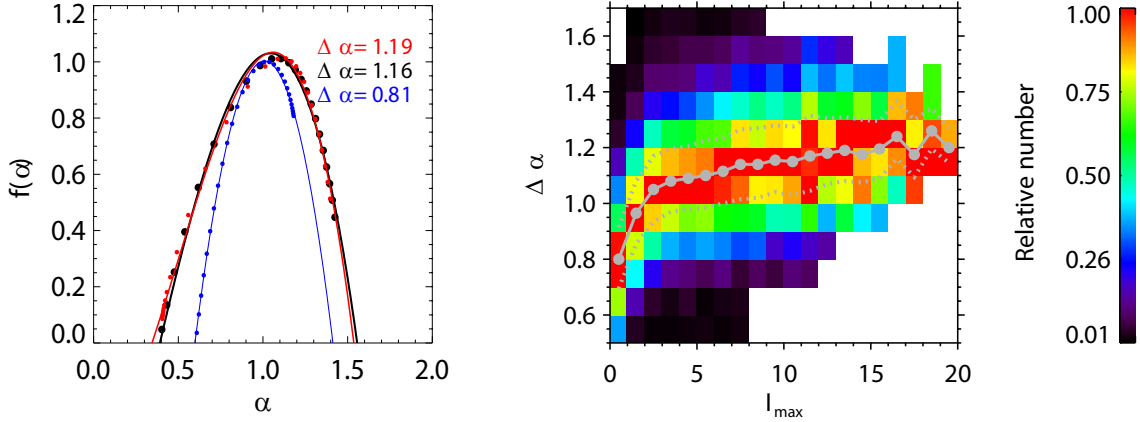


Figure 10: **Left:** Multifractal singularity spectra $f(\alpha)$ versus α observed in the slow wind (points) with red for the intermittent interval shown in Figure 4 ($I_{max} = 13.09$), black for the intermittent interval shown in Figure 2 ($I_{max} = 4.10$), and blue for the quiet interval shown in Figure 5 ($I_{max} = 1.44$). The solid lines denote the cubic polynomial fitting to the observations. The width of each singularity spectrum $\Delta\alpha = \alpha_{max} - \alpha_{min}$ is marked in the panel. **Right:** Joint distribution of I_{max} and $\Delta\alpha$ for the 33,261 intervals with $\lambda_1/\lambda_2 > 3$. For a given pixel, the color denotes relative number, which is the number of the cases normalized by the maximum number among the corresponding I_{max} bin. The pixels containing no more than 10 cases are ignored. The gray solid circles represent average $\Delta\alpha$ in each I_{max} bin. The dotted gray lines represent the upper/lower quartiles.

4. Another crucial point is the definition of the threshold above which an interval is considered intermittent, i.e., the PVI threshold. Indeed, the authors used a threshold of 2 since “The Gaussian distributions are located between the PVI range $[-2, 2]$ ”. However, the definition of PVI is indeed a measure of the level of fluctuations with respect to an average level, i.e., something that resembles a standardization procedure. Did the authors performed the sensitivity of the results based on the choice of the threshold for identifying an intermittent interval?

Reply: Thanks for the suggestion! According to the suggestion, we check the sensitivity of the results on the choice of PVI threshold. We add the following paragraph and a new figure in original line 316: “We also check the sensitivity of the results based on the choice of the threshold for identifying an intermittent interval. The threshold is changed from the original PVI range $[-2, 2]$ into two new ranges $[-1, 1]$ and $[-3, 3]$. The results are shown in Figure 12. The left panels and right panels correspond to the thresholds $[-1, 1]$ and $[-3, 3]$ for identifying an intermittent interval, respectively. They are plotted in the same format as

Figure 6. The black curves in the lower two panels are both the exponential function $\alpha_B = 0.4 \exp(-I_{max}/5) - 2.02$, which is adopted from Figure 6. It is found that the black curve obtained from the original threshold $[-2, 2]$ can still match the new results well. Therefore, our result shown in Figure 6 is robust, and is not sensitive to the choice of the threshold for identifying intermittent intervals.”

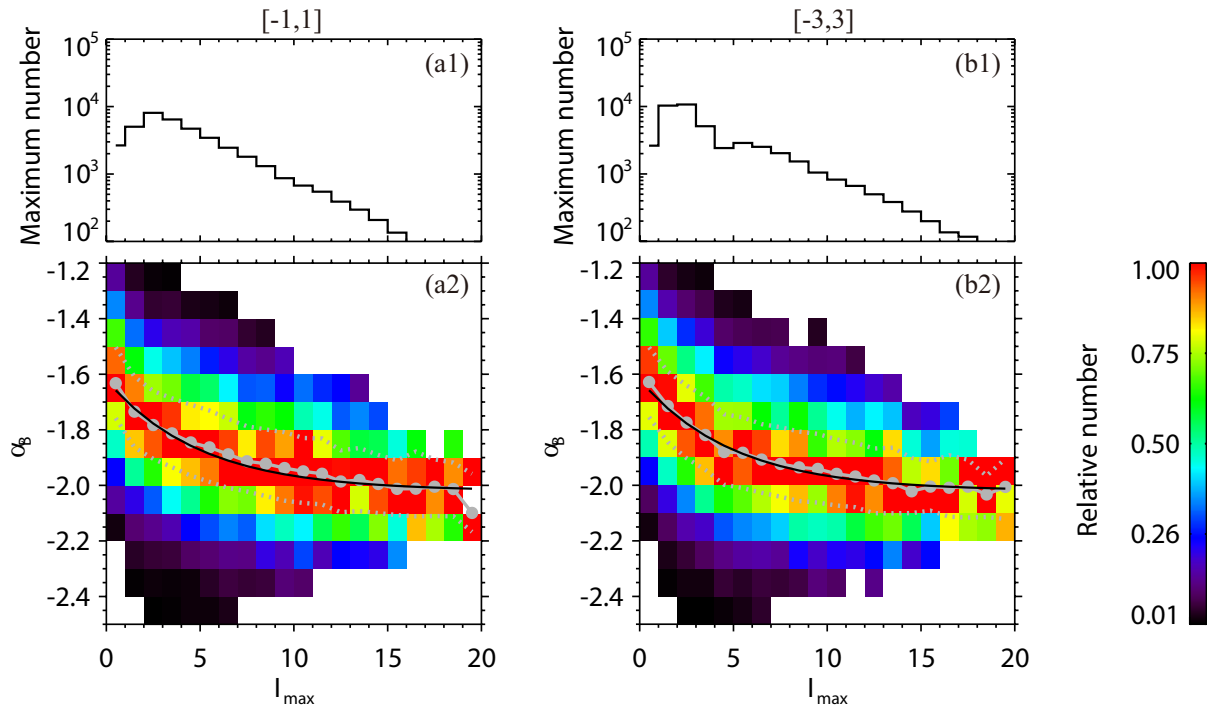


Figure 12: Panels (a1)(a2) and panels (b1)(b2) are plotted in the same format as Figure 6, but for the PVI thresholds $[-1, 1]$ and $[-3, 3]$ for identifying an intermittent interval, respectively. The black curves in panels (a2) and (b2) are both the exponential function $\alpha_B = 0.4 \exp(-I_{max}/5) - 2.02$, which is adopted from Figure 6.

Additional detailed comments

Line 3: I would suggest to clarify that “an analytical/functional relationship...” has not been shown yet.

Reply: Thanks! Revised.

Line 4: the term “intermittency magnitude” could be biased by the definition, it would

be better to use the classical notation of “intermittency level”.

Reply: Thanks! We replace the term “intermittency magnitude” by “intermittency level” throughout the text.

Line 59: again here an analytical relation has not been shown yet, while several cascade modes have found intermittency corrections to the spectral slope.

Reply: Thanks for the suggestion! The original sentence is replaced by the new ones: “There is a huge literature on the correction of the scaling properties due to intermittency, and many improved cascade models have been proposed to revise the original Kolmogorov results. However, no analytical relationship between the magnetic spectral index and the level of intermittency has been shown so far.”

Lines 74-75: I am not sure the whole interval from 2005 and 2013 is characterized by an undisturbed solar wind (there are different transients indeed). I would suggest to state that the selected intervals all correspond to undisturbed solar wind conditions (if this is the case).

Reply: Thanks! We delete the phrase “in the undisturbed solar wind”, and the sentence is revised as “During this period, the WIND spacecraft was located at the Lagrangian point L1.”

Line 77: please change “~” with “—”.

Reply: Thanks! Revised.

Line 124: is it 15 s or 150 s as stated in line 114?

Reply: The width of the intermittent structure is recorded as 15 s. We revise the sentence to clarify this point: “The two vertical dotted lines mark the beginning time ($t_B=01:44:19$) and ending time ($t_E=01:44:34$) of the intermittent structure, respectively. ... Accordingly, the width of this intermittent structure obtained from $t_E - t_B$, during which the condition $|PVI_z| > 2$ satisfies, is recorded as 15 s (5 data points).”

Line 209: did you check that this is not an Alfvénic stream and then the spectrum should be f-3/2? If this is the case, this means that there is an intermittency correction.

Reply: According to the suggestion, we check the Alfvénicity of this case,

and find that it is not an Alfvénic interval with low normalized cross helicity $\sigma_c = 0.34$ and low Alfvén ratio $\gamma_A = 0.47$. We add the following sentence to clarify this point: “We check the Alfvénicity of this case, and find that it is not an Alfvénic interval with low normalized cross helicity $\sigma_c = 0.34$ and low Alfvén ratio $\gamma_A = 0.47$. It’s worth noting that for an Alfvénic interval, if the magnetic spectrum scales as $f^{-5/3}$, an intermittency correction could be considered.”

Line 232: which kind of discontinuities? This is important to understand which situation is presented.

Reply: The techniques used for the data analysis have strong influence on the classification of different types of discontinuities in the solar wind. We add the following sentences in Line 232: “In previous studies, the discontinuities in the solar wind have been identified mainly as rotational discontinuities (e.g., Neugebauer et al., 1984; Tsurutani and Ho, 1999; Wang et al., 2013; Liu et al., 2021). However, in some other studies, the discontinuities have been identified mainly as tangential discontinuities, depending on the different techniques used for data analysis (e.g., Horbury et al., 2001; Knetter et al., 2004; Riazantseva et al., 2005).”

Line 235: could the maximum value be biased by the anisotropy of fluctuations? I mean is this really representative of something new or simply a reflection of a spectrum of anisotropic fluctuations?

Reply: Thanks for the suggestion! According to the suggestion, we perform a check about whether the intermittency level I_{max} could be biased by the anisotropy of fluctuations. In Figure R1 shown below, we present the joint distribution of θ_{LX} (θ_{LY} , θ_{LZ} , and θ_{LB} defined in the reply to “Major comments #2”) and intermittency level I_{max} in the similar format as Figure 9 shown above. From the average value of I_{max} in each angle bin (gray dots) of panels (a)(b)(c) of Figure R1, we can see that the intermittency level I_{max} appears to be not dependent on the direction of the predominant fluctuations. In panel (d), we see that the average I_{max} (~ 4.0) for $\theta_{LB} > 70^\circ$ is slightly larger than the average I_{max} (~ 2.6) for $20^\circ < \theta_{LB} < 60^\circ$. However, from Figure 9(d2), it has been found that the spectral index α_B nearly does not change with θ_{LB} . Accordingly, we add the following sentence in original line 235: “We have checked about whether the intermittency level I_{max} could be biased by the anisotropy of fluctuations. It is found that the intermittency level I_{max} appears to be not dependent on the direction of the predominant fluctuations (figure not shown here, since it is similar as Figure 9).”

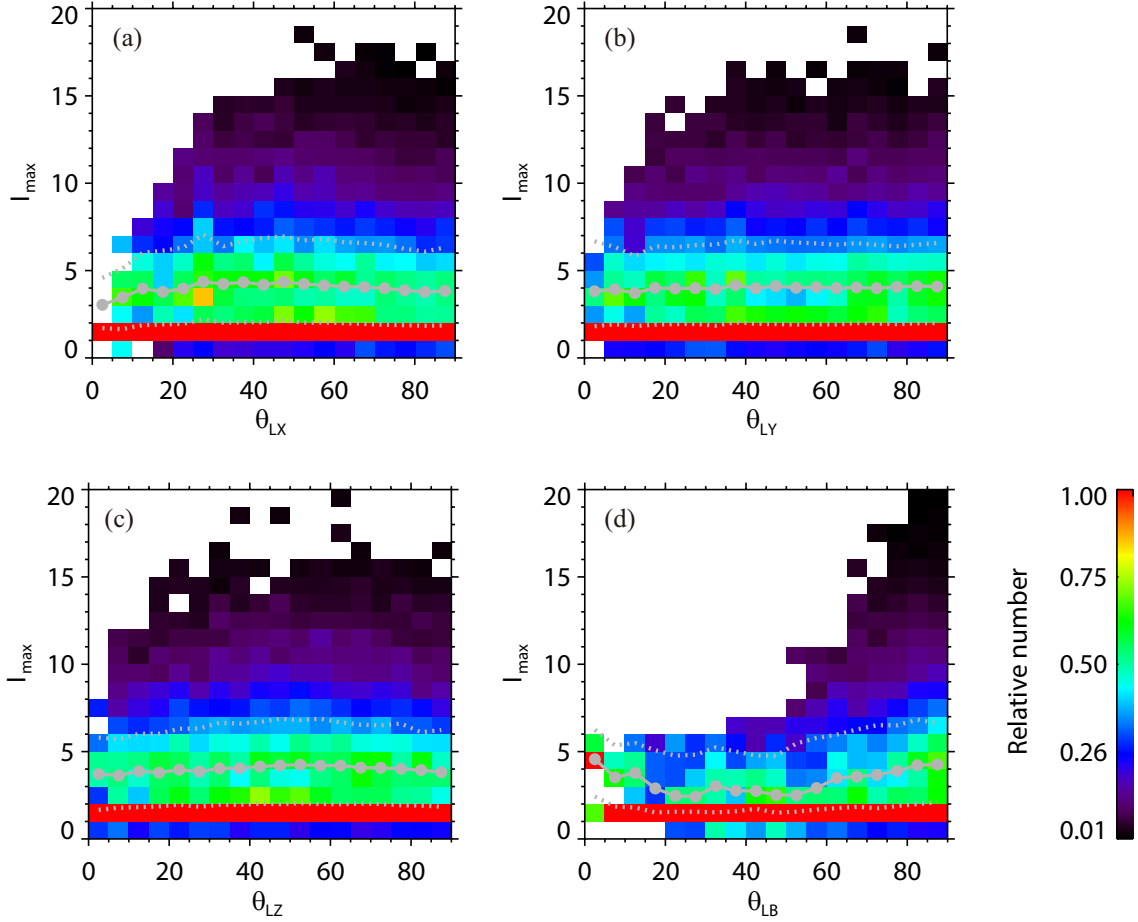


Figure R1: (a) Joint distribution of θ_{LX} and intermittency level I_{max} for the 33,261 intervals with $\lambda_1/\lambda_2 > 3$. For a given pixel, the color denotes relative number, which is the number of the cases normalized by the maximum number among the corresponding θ_{LX} bin. The maximum number of each bin is shown in panel (a1) of Figure 9. The pixels containing no more than 10 cases are ignored. The gray solid circles represent average I_{max} in each θ_{LX} bin. The dotted gray lines represent the upper/lower quartiles. Panels (b) is plotted in the same format as panel (a) but for θ_{LY} . Panels (c) corresponds to θ_{LZ} . Panel (d) corresponds to θ_{LB} .

Line 244: there is a recent literature on the scaling properties and intermittency levels with Parker Solar Probe (see papers by Alberti, Cuesta, Matthaeus).

Reply: Thanks for the suggestion! We add the reference papers into the manuscript at line 244 as following: “Recently, there are several papers on the scaling properties and intermittency levels with Parker Solar Probe (e.g., Alberti

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