Disappearance of Anisotropic Intermittency in Large-amplitude MHD Turbulence and Its Comparison with Small-amplitude MHD Turbulence

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Received 2017 December 14; revised 2018 January 31; accepted 2018 February 1; published 2018 March 8

Abstract

Multi-order structure functions in the solar wind are reported to display a monofractal scaling when sampled parallel to the local magnetic field and a multifractal scaling when measured perpendicularly. Whether and to what extent will the scaling anisotropy be weakened by the enhancement of turbulence amplitude relative to the background magnetic strength? In this study, based on two runs of the magnetohydrodynamic (MHD) turbulence simulation with different relative levels of turbulence amplitude, we investigate and compare the scaling of multi-order magnetic structure functions and magnetic probability distribution functions (PDFs) as well as their dependence on the direction of the local field. The numerical results show that for the case of large-amplitude MHD turbulence, the multi-order structure functions display a multifractal scaling at all angles to the local magnetic field, with PDFs deviating significantly from the Gaussian distribution and a flatness larger than 3 at all angles. In contrast, for the case of small-amplitude MHD turbulence, the multi-order structure functions and PDFs have different features in the quasi-parallel and quasi-perpendicular directions: a monofractal scaling and Gaussian-like distribution in the former, and a conversion of a monofractal scaling and Gaussian-like distribution into a multifractal scaling and non-Gaussian tail distribution in the latter. These results hint that when intermittencies are abundant and intense, the multifractal scaling in the structure functions can appear even if it is in the quasi-parallel direction; otherwise, the monofractal scaling in the structure functions remains even if it is in the quasi-perpendicular direction.

Key words: magnetohydrodynamics (MHD) – methods: numerical – solar wind – turbulence

1. Introduction

Solar wind turbulence is often observed to involve strong intermittency, which can manifest itself as small-scale coherent structures. Intermittency can cause uneven energy transfer rates, enhanced energy dissipation, anisotropic temperature, as well as energy spectra scaling anisotropy (Osman et al. 2012; Wang et al. 2013, 2014; Wu et al. 2013; Haynes et al. 2014; Pei et al. 2016). It can also intensify the current sheet in turbulent plasmas, and therefore enhance the transport of particles and momentum. Therefore, intermittency plays key roles in the turbulent dynamics.

Intermittency of velocity, magnetic field, and density has been widely reported in the solar wind turbulence since the 1990s (e.g., Burlaga 1991, 1992; Marsch & Liu 1993; Marsch & Tu 1994, 1997; Tu et al. 1996; Horbury et al. 1997; Bruno et al. 1999, 2001, 2003; Sorriso-Valvo et al. 1999, 2005; Salem et al. 2009; Osman et al. 2012; Wu et al. 2013; Chen et al. 2014; Wang et al. 2014; Pei et al. 2016). To characterize the intermittency, the multifractal scaling in the structure functions are suggested. For turbulence, which is self-similarity or scale invariance, and is thus in the absence of intermittency, the scaling exponent ζ(m) of structure functions is proposed to linearly vary with its order moment m as m/3 (a Kolmogorov-like scaling) or m/4 (a Kraichnan-like scaling), which are signatures of monofractals. When the effects of intermittency are taken into consideration, the profile of the scaling exponent ζ(m) is presented to behave differently from the linear one, bending toward smaller values than m/3 or m/4, which are signatures of multifractals. With Voyager data at 8.5 au, Burlaga (1991) showed that velocity fluctuations reveal multifractal structure on timescales from 0.85 to 13.6 hr, a result that indicates the existence of intermittent turbulence in the solar wind. Burlaga (1992) further demonstrated the existence of multifractal structure in the fluctuations of the magnetic field strength, temperature, and density in the recurrent flows at 1 au. Derived from Helios data, Marsch & Liu (1993) found a multifractal scaling of the multi-order structure functions of the flow velocity and Alfvén velocity in the inner solar wind between 0.3 and 1.0 au, and provided further evidence for the intermittent nature of solar wind fluctuations.

Intermittency is also characterized by a non-Gaussian probability distribution function (PDF) of fluctuations. With decreasing space/timescales, the PDFs of fluctuations deviate from the Gaussian distribution, and grow a substantial extended tail on both wings, which is attributed to intermittency. Marsch & Tu (1994) reported the PDFs of both velocity and magnetic field, which are calculated from the time series of Helios data obtained in 1976 at heliocentric distances near 0.3 au, are normally distributed approximating a Gaussian function for a comparatively long time lag, while they are super-Gaussian in the center part, sub-Gaussian in the near-wing part, and super-Gaussian again in the far-wing part as compared to the
Gaussian distribution with the same standard deviation for shorter time lags. The non-Gaussian features at short time lags were thought to be direct evidence for spatial intermittency of the fluctuations. Sorriso-Valvo et al. (1999) showed that the non-Gaussian behavior of the PDFs of solar wind bulk speed and magnetic field intensity fluctuations can be fitted by a convolution of Gaussians whose variances are distributed according to a log-normal distribution. Using high time resolution Faraday cup measurements from the Spektr-R spacecraft, Chen et al. (2014) found that the PDFs of density fluctuations in the solar wind are highly non-Gaussian over kinetic scales, and do not show large changes in shape with scale.

The presence of the background magnetic field in the solar wind breaks the isotropy existing in hydrodynamics, and results in the power spectral density and correlation function of fluctuations depending on the angle of the local magnetic field direction to the solar wind field (Horbury et al. 2008; Osman et al. 2011). The intermittency may be anisotropic, and recently structure function scaling is found to be different parallel and perpendicular to the local magnetic field. Using measurements from the STEREO spacecraft in the fast ambient solar wind, Osman et al. (2014) conducted a multi-order multiscale analysis of spatial anisotropy in the inertial range of magnetohydrodynamics (MHD) turbulence. They showed that when measuring parallel to the local magnetic field direction, the multi-order structure functions of the magnetic and Elsässer field fluctuations display a monofractal scaling, which is distinct from the multifractal scaling of the multi-order structure functions with wavevectors perpendicular to the local field. Pei et al. (2016) found that after eliminating the intermittency with the Local Intermittency Measure method, the multifractal scaling of the multi-order structure functions disappears, and the multi-order structure functions show the monofractal scaling law in all the directions.

Meanwhile, many numerical simulations have been conducted to study intermittency in the MHD turbulence (Maron & Goldreich 2001; Müller et al. 2003; Beresnyak & Lazarian 2006; Mason et al. 2006; Uritsky et al. 2010; Yang et al. 2015, 2017a, 2017b; Zhang et al. 2015; Zhdankin et al. 2015). In both decaying and forced simulations of the MHD turbulence with a strong guide magnetic field, Maron & Goldreich (2001) observed a spectral index that was flatter than −5/3, and speculated that spectra could be shallow due to intermittency. Müller et al. (2003) conducted simulations of the decaying and forced magnetohydrodynamic MHD turbulence without and with a global guide magnetic field, and pointed out that an intermittency model based on a log-Poisson approach could describe the observed structure function scalings. Zhdankin et al. (2015) performed a statistical analysis of four-dimensional spatio-temporal dissipative structures in driven incompressible MHD turbulence, and found that these structures exhibited robust power-law probability distributions and scaling relations. Based on the simulation results of the driven compressible MHD turbulence, Yang et al. (2017b) used the wavelet technique to identify intermittency, and found that after removal of the intermittency, the quasi-perpendicular spectral index returns back to the Kolmogorov value from the value for the originally shallower spectrum.

In this work, based on the numerical simulations of the driven large-amplitude and small-amplitude MHD turbulence with a global guide magnetic field (Yang et al. 2017a, 2017b), we examine the scaling behavior of multi-order structure function of the magnetic field, the PDFs of the magnetic field, and their dependence on the direction of the local magnetic field. The content of this paper is organized as follows. In Section 2, a general description of the numerical MHD model is given. Section 3 describes the numerical results, and the last section is reserved for a summary and discussion.

2. Numerical MHD Model

The details of the three-dimensional (3D) numerical MHD model have been described in Yang et al. (2017a). Here, we describe its basic setup and some modifications for the current study. The numerical MHD model solves the conservation of mass, momentum, and energy together with the induction equation as follows:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (1)
\]

\[
\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left[ \rho \mathbf{u} \mathbf{u} + \left( \frac{p + \frac{1}{2} B^2}{\gamma - 1} \right) \mathbf{I} - \mathbf{BB} \right] = \mathbf{f}_e, \quad (2)
\]

\[
\frac{\partial e}{\partial t} + \nabla \cdot \left[ \mathbf{u} (e + \frac{1}{2} B^2) - (\mathbf{u} \cdot \mathbf{B}) \mathbf{B} \right] = \nabla \cdot (\mathbf{B} \times \mathbf{j}), \quad (3)
\]

\[
\frac{\partial B}{\partial t} + \nabla \cdot (\mathbf{u} B - B \mathbf{u}) = \eta \nabla^2 \mathbf{B} + \mathbf{f}_b, \quad (4)
\]

where \(e = (1/2) \rho \mathbf{u}^2 + p/\gamma - 1 \right) + (1/2) \mathbf{B}^2 \), \( j = \nabla \times \mathbf{B} \), \( \gamma \) is the adiabatic index; \( \eta = 0.001 \) is the magnetic resistivity. \( \mathbf{f}_e \) and \( \mathbf{f}_b \) are large-scale random drivers. They are also uncorrelated, and satisfy \( \nabla \cdot \mathbf{f}_e = 0 \) as well as \( \nabla \cdot \mathbf{f}_b = 0 \).

The computation domain is a cube with a side length of \( 2\pi \) and a resolution defined by \( 512 \times 512 \) grid points. Periodic boundary conditions are applied at the computational boundaries. The simulation domain is initially without fluctuations, and the global guide magnetic field \( \mathbf{B}_0 \) is set to 1.00. To solve the above equations, we use a third-order piecewise parabolic method for reconstruction and an approximate Riemann solver of Harten–Lax–van Leer Discontinuities for calculation of numerical fluxes, and the constrained transport algorithm to guarantee the divergence-free state of the magnetic field.

Three independent parameters, an initial mean density \( \rho_0 \), a characteristic length \( L_0 \), and a characteristic Alfvén speed \( v_A \), are used to normalize the MHD equations. Other variables are normalized by their combinations. To be comparable with parameters of solar wind turbulence at 1 au, here, \( \rho_0 = N_0 m_p \) with \( N_0 = 5 \text{ cm}^{-3} \) being number density and \( m_p \) being the mass of a proton; \( L_0 \) is set to \( 2 \times 10^8 \text{ Mm} \), and \( v_A = 100 \text{ km s}^{-1} \) (Yang et al. 2017c). With these parameters, the length of the computation domain is \( 2\pi L_0 = 1.26 \times 10^9 \text{ Mm} \), and the large-scale random drivers are applied in Fourier space at \( k < 3.5 \times 1.0/L_0 \right) = 1.75 \times 10^{-3} \text{ Mm}^{-1} \).
By adjusting the magnitudes of $f_v$ and $f_b$, we can obtain the MHD turbulences with different amplitudes of fluctuations. Here, we study both the large amplitude of the turbulence, with the root-mean-square (rms) amplitude of the magnetic field in the statistically stationary state being about 0.72, and the small amplitude of the turbulence, with the rms amplitude of magnetic field being around 0.10, by calculating the multi-order structure functions and PDFs of magnetic field.

Figure 1. Structure functions of the magnetic field with different orders ($m = 2, 3, 4, 5$) as a function of angle $\theta$ and scale $r$ for the large-amplitude turbulence $\delta B = 0.72$ (left panels) and the small-amplitude turbulence $\delta B = 0.10$ (right panels).
For a snapshot at any time, pairs of points in the simulation box are picked at random, and are employed to compute structure functions and PDFs at different angles between the spatial separation direction and the local mean magnetic field direction. The $m$th order structure function is defined by

$$S^m(\theta, r) = \frac{1}{N} \sum_{i=1}^{N} |B(l + r) - B(l)|^m,$$

where $l$ is position vector of points, $r$ is separation vector between a pair of points, $\theta$ is angle between $r$ and the local mean magnetic field, $B_{\text{local}}$, computed by

$$B_{\text{local}} = \frac{B(l + r) + B(l)}{2},$$

and $N$ is total number of pairs at $\theta$ and $r$. At certain $\theta$ and $r$, most of the structure function values are the average of tens of thousands of pairs of points. To calculate the PDFs of the magnetic field, the differences of magnetic field component $B_\parallel(l + r) - B_\parallel(l)$ are selected in order to see symmetric behavior in the fluctuations. It should be noted that, except for the results in Figure 8, the results presented below are at the time when the simulated turbulences are in a statistically stationary state.

3. Numerical Results

Figure 1 presents the second-, third-, fourth-, and fifth-order structure functions of the magnetic field as a function of angle $\theta$ and scale $r$ for the large-amplitude turbulence $\delta B = 0.72$ (left panels) and the small-amplitude turbulence $\delta B = 0.10$ (right panels). It can be seen that similar to the solar wind observation (Chen et al. 2011; Pei et al. 2016) and previous simulations (Cho & Vishniac 2000), the structure functions change significantly with the angle $\theta$ both for the large-amplitudes and small-amplitude turbulence. At the same scale $r$, the magnitudes of the structure functions increase with $\theta$, and this increase seems to saturate before the angle $\theta = 40^\circ$ and does not continue to rise after $\theta = 40^\circ$. Thus, the contours of the
Structure functions in the $\theta$-$r$ plane are elongated in the quasi-parallel direction, i.e., $0^\circ < \theta_{RB} < 10^\circ$, which indicates the existence of an anisotropy of the structure functions. As the order of the structure functions grows, their elongation in the quasi-parallel direction is more evident, and with the same order of the structure functions, the small-amplitude turbulence displays more obvious anisotropy of the structure functions than the large-amplitude turbulence.

Here we will focus on the scaling behavior of the structure functions for each $\theta$, which is represented by

$$S^m(\theta, r) \propto r^{\zeta(m)},$$

where $\zeta(m)$ are the scaling exponents. Figure 2 shows the structure functions of the magnetic field with different orders as a function of $r$ for the large-amplitude and small-amplitude turbulences, with the structure functions for each $\theta$ being stacked with a uniform offset. This figure tells us that in the range $18 < r < 70$ (the unit of $r$ is $2 \pi L_0/512 = 24.5$ Mm), the second-, third-, fourth-, and fifth-order structure functions display power laws for each $\theta$ for both the large-amplitude and small-amplitude turbulence, and the range is considered to be within the inertial range of the driven turbulences. Over this scale range, linear fits, which are shown as red lines in this figure, are performed for the structure functions on a log–log plot, and the corresponding scaling exponents as well as their uncertainties are obtained.

Figure 3 presents the relation between the scaling exponent $\zeta$ and the order moment $m$ for each $\theta$ for both the large-amplitude and small-amplitude turbulences, with error bars denoting the uncertainty of the scaling exponents. It can be seen that for the large-amplitude and small-amplitude turbulences, the profiles of $\zeta_B(m)$ behave differently in the quasi-parallel direction (marked as $\theta = 5^\circ$ and shown as the red lines in this figure), although the profiles look similar in the quasi-perpendicular direction (marked as $\theta = 85^\circ$ and shown as the blue lines in this figure). For the large-amplitude turbulence (left in Figure 3), the magnetic field fluctuations in all directions display nonlinear scaling exponents $\zeta_B$, which indicates a multifractal scaling of the multi-order structure functions. In contrast, for the small-amplitude turbulence (right in Figure 3), the behaviors of the scaling exponents change from $\theta = 5^\circ$ to $\theta = 85^\circ$. In the quasi-parallel direction of $\theta = 5^\circ$, the scaling exponent $\zeta(m)$ of the structure function linearly varies with its order moment $m$, which indicates a monofractal scaling of the multi-order structure functions. As $\theta$ increases, the change of $\zeta_B$ with $m$ recovers a nonlinear relation.

Figure 4 shows the relation between the scaling exponent $\zeta$ and the order moment $m$ for the velocity ($\zeta_u$ left panel) and density ($\zeta_\rho$, right panel) for the large-amplitude turbulence $B_\parallel = 0.72$. Error bars represent the uncertainty of the scaling exponents. In each panel, the red line denotes the relation in the quasi-parallel direction of $\theta = 5^\circ$, and the blue line is the relation in the quasi-perpendicular direction of $\theta = 85^\circ$.
To evaluate the degree of intermittency, we plot the scale dependence of the flatness as shown in Figure 6 for the large-amplitude and small-amplitude turbulences, as flatness can reflect the peakedness and the tailedness of the probability distribution of a certain parameter. Here, the flatness is defined as

$$\text{Flatness}(\theta, r) = \frac{\langle (B_x(I + r) - B_x(I))^4 \rangle}{\langle (B_x(I + r) - B_x(I))^2 \rangle^2},$$

where the brackets denote the average of the $N$ pairs of points. When the flatness is larger than 3, the PDFs of $B_x$ are peaked around the average value and also extended with heavy tails on both sides. The left panel of Figure 6 displays the variation of the flatness with $r$ in the quasi-parallel direction, and the right panel is in the quasi-perpendicular direction.

From this figure, it is readily seen that in the quasi-parallel direction, the large-amplitude turbulence displays dramatic rise of the flatness as the scale decreases. The flatness significantly deviates from 3, which means that the driven fluctuation in this direction becomes intermittent. However, the flatness for the small-amplitude turbulence is close to 3 at the scale greater than 30, and its maximum comes to only about 3.7 at $r = 21$, which indicates that the fluctuations at these scales are not so significantly intermittent. In the quasi-perpendicular direction, the behaviors of the flatness with $r$ are similar for both large-amplitude and small-amplitude turbulences. At the large scale, the flatness is rather close to 3, while it grows quickly and becomes larger with the smaller scale. It is noted that although for the small-amplitude turbulence flatness is always smaller in the quasi-parallel direction than that in the quasi-perpendicular direction, for the large-amplitude turbulence a relatively larger flatness exists when sampled quasi-parallel than that when measured quasi-perpendicularly to the local magnetic field, which may be as a result of the smaller second-order moment in the quasi-parallel direction than that in the quasi-perpendicular direction.

Figure 5. PDFs of the magnetic field fluctuations $B_x$ scaled by their standard deviation ($\sigma$) at different scales $r$ in the quasi-parallel (left panels) and quasi-perpendicular (right panels) directions for the large-amplitude turbulence $\delta B = 0.72$ (upper panels) and the small-amplitude turbulence $\delta B = 0.10$ (lower panels). The Gaussian profiles are plotted for comparison as the colored dotted curves.
To see the differences of intermittency in the quasi-parallel and quasi-perpendicular directions, we plot the distributions of the normalized total variance of increments (TVI) in Figure 7 for the large-amplitude and small-amplitude turbulences. TVI, as an indicator of intermittency (Zhang et al. 2015), is defined as

\[
\text{TVI} = \frac{\left| \Delta B \right|}{\langle |\Delta B| \rangle},
\]

where

\[
|\Delta B| = \sqrt{\sum_{\alpha \in \{x,y,z\}} (\partial B_\alpha / \partial x)^2}.
\]

From Figure 7, it can be seen that for the large-amplitude turbulence, the isosurface of TVI (=16) exhibits complicated 3D shape, and does not have a preferred direction, while for the small-amplitude turbulence, the isosurface of TVI (=16) predominantly orients in the z-direction, shown by the imposed guide field lies. Also, for the large-amplitude turbulence, the distributions of TVI show no evident differences between the x–z or y–z plane and the x–y plane.

\[
\frac{\partial B_\beta}{\partial x} = \frac{B_\beta(i + w, j, k) - B_\beta(i - w, j, k)}{2w\delta x},
\]

with \(\delta x\) being the grid distance, \(B_\beta\) denotes the corresponding component of the magnetic field, and \(w(=3)\) is the width.
For the small-amplitude turbulence, the large TVI is significantly elongated in the $x$–$z$ or $y$–$z$ plane.

Figure 8 shows the profiles of scaling exponent $\zeta$ of the magnetic structure functions and flatness of the magnetic PDFs in both the quasi-parallel and quasi-perpendicular directions for the small-amplitude turbulence $\delta B = 0.10$ at $t = 20$. From this figure, it can be seen that, at this time, the profile of the scaling exponent basically varies linearly with the order moment $m$, with the flatness at all scales close to 3, whether it is in the quasi-parallel direction or in the quasi-perpendicular direction.

4. Summary and Discussion

In this study, based on the simulations of the driven compressible MHD turbulence with a global guide magnetic field, we investigate the multi-order structure functions and the PDFs of the magnetic field for both the large-amplitude and small-amplitude fluctuations. In particular, we study how the scaling exponent of the structure function varies with the order moment $m$ and the angle $\theta$ to the local mean magnetic field as well as their association with PDFs.

The numerical results show that in both the large-amplitude and small-amplitude turbulence, the multi-order structure functions display the anisotropy, i.e., their magnitudes increase significantly toward the directions perpendicular to the local magnetic field, and thus their contours are elongated in the quasi-parallel direction. The anisotropy rises with the order of the structure functions, and the anisotropy in the small-amplitude turbulence is more evident than that in the large-amplitude turbulence. In the range $18 < r < 70$, the structure functions display power laws, and by linear fits to them on a log–log plot, the relations between the scaling exponent $\zeta$ and the order moment $m$ are obtained for each $\theta$. For the large-amplitude turbulence, the magnetic field fluctuations display the multifractal scaling of the multi-order structure functions in all angles between the spatial separation direction and the local mean magnetic field direction, which is the feature of intermittency, while for the small-amplitude turbulence, the monofractal scaling exists in the quasi-parallel direction, and the multifractal scaling eventually appears in the quasi-perpendicular direction.

The numerical results also show that for the large-amplitude turbulence, the PDFs of the magnetic field fluctuations $B_x$ changes significantly from the large scales to the small scales in the quasi-parallel and quasi-perpendicular directions. At the large scales, the PDFs of $B_x$ approach to the Gaussian distribution, with a flatness close to 3, and at the small scales, the PDFs of $B_x$ display a long tail, with the flatness largely deviating from 3. Also, a relatively larger flatness exists in the quasi-parallel direction than that in the quasi-perpendicular direction. In contrast, for the small-amplitude turbulence, the PDFs of $B_x$ are close to the Gaussian distribution for all scales in the quasi-parallel direction, which means that the fluctuations in this direction are not less intermittent. However, with the scale decreasing, the non-Gaussian tail of the PDFs becomes evident in the quasi-perpendicular direction, and the intermittency becomes intense.

These results verify that the above two ways to characterize intermittency are consistent. When intermittencies are abundant and intense in the quasi-parallel or quasi-perpendicular direction, the multi-order structure functions present a multifractal scaling, and meanwhile the PDFs significantly deviate from the Gaussian distribution. In such a circumstance, intermittencies become hard to distinguish between in the quasi-parallel and quasi-perpendicular directions. When intermittencies are scare and weak, the multi-order structure functions display a monofractal scaling, and meanwhile the PDFs are close to the Gaussian distribution even if it is in the quasi-perpendicular direction. It should be noted that when the local averaged field, $B_{\text{local}}$, is computed on the scale larger than that determining the fluctuations ($r$), that is, $B_{\text{local}} = (B(l-r-r) + B(l-r) + B(l) + B(l+r) + B(l+r+r))/5$, the relation between the scaling exponent $\zeta$ and the order moment $m$ for each $\theta$ remains almost unchanged. This result suggests that the relation of $\zeta(m, \theta)$ for both weak and strong turbulence levels are robust, and independent of the definition of the local mean magnetic field.

The potential implications of these results may be substantial for astronomy as realistic interstellar medium
turbulence usually has the large-amplitude fluctuations (Beresnyak & Lazarian 2006). However, some problems still remain to be solved in the future. The first is about the nature of intermittency. Based on the use of wavelets, Bruno et al. (2001) studied the characterization of intermittency events in the solar wind. By a single case study of magnetic field intermittency, they found that this event was located at possibly the border between two adjacent flux tubes. Do all the intermittencies have such properties? A complete analysis based on the 3D simulation data is necessary to identify and classify intermittency. Further questions involve the structure of intermittency. Based on the use of wavelets, Bruno et al. (1999) showed that the intermittency has such properties? A complete analysis based on the 3D simulation data is necessary to identify and classify intermittency. Does intermittency behave as a rapid increase and then a rapid decrease of physical parameters, or as a steep jump of physical parameters like discontinuities? As we know, the first type of structure has a greater influence on the structure functions at smaller scales, while the second type has a greater effect at the larger scale. At last, this work shows that the fluctuations become very large, there is a change in the parallel magnetic field fluctuations as well as the plasma fluctuations. The realistic parallel dynamics involving various physical mechanisms may be altered in response to the enhancement of parallel magnetic field fluctuations. On the other hand, gradients in parallel currents may arise and drive vorticity, which may be coupled with density fluctuations. On the other hand, due to the existence of electron heat conduction, the thermal pressure gradient along the parallel direction may decrease, and the compressibility of parallel oscillations may be prone to damping, which causes the parallel fluctuations to become weak again yielding to a monofractal scaling of high-order structure functions. Future investigations may be conducted to address these issues.

This work is supported by NSFC grants under contracts 41774157, 41674171, 41474147, 41731067, 41574168, 41421003, 41504130, and the Specialized Research Fund for State Key Laboratories. The work was carried out at National Supercomputer Center in Tianjin, China, and the calculations were performed on TianHe-1 (A). J.S.H. is also supported by the National Young Talent Support Program of China. Both L.-P.Y. and L.Z. contributed equally to this work and should be considered as co-first authors. L.-P.Y., L.Z. and J.-S.H. are the co-corresponding authors, who are available for the contact regarding all the aspects of this work.

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