Intermittent Anisotropic Turbulence Detected by THEMIS in the Magnetosheath

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Abstract

Following our previous study of Time History of Events and Macroscale Interactions during Substorms (THEMIS) data, we consider intermittent turbulence in the magnetosheath depending on various conditions of the magnetized plasma behind the Earth’s bow shock and now also near the magnetopause. Namely, we look at the fluctuations of the magnetosheath is compressible even at a large scale and the bow shock acts as a source of intense fluctuations the conditions are propitious to turbulence in this region (Perri et al. 2009). In addition, using kinetic simulations, Karimabadi et al. (2014) have demonstrated that turbulent processes at shocks could be related to reconnection processes. Obviously, for small scales below the ion gyroradius in the magnetosheath inertial kinetic Alfvén waves may also be active (Chen & Boldyrev 2017). We are aware of the advanced MHD simulations, including Hall effects. But, in spite of this progress, the physical mechanisms of turbulent behavior are still not sufficiently well understood even at the standard inertial range. Therefore, we should still use phenomenological models to describe multiplicative processes, which lead to complex behavior of the plasma.

In our previous studies, using a multifractal model (Macêk 2007; Macêk & Szczepaniak 2008) applied to solar wind turbulence, we have considered the intermittent nature of turbulence in the heliosphere (Macêk & Wawrzaszek 2009; Macêk et al. 2011, 2012), also beyond the ecliptic plane (Wawrzaszek & Macêk 2010; Wawrzaszek et al. 2015), and even to the heliospheric boundaries (Burlaga et al. 2013; Macêk et al. 2014). It appears that space plasmas can exhibit substantial deviations from Gaussian distributions resulting in higher moments (especially the fourth moment, kurtosis), which are often considered signatures of intermittency (e.g., Frisch 1995).

1. Introduction

The complex nature of space plasmas resulting from intermittent turbulence is still a challenge for contemporary science, as recently noted by Chang (2015). Naturally, turbulence often appears in space and astrophysical plasmas, for example, in the solar wind and interstellar medium, including interstellar and planetary shocks. As has been recently argued, the solar wind can be considered a turbulence laboratory (Bruno & Carbone 2013, 2016). We also know that the shocks in the space environment are usually collisionless. This means that processes responsible for shock formation are different from those in ordinary fluids (Kivelson & Russell 1995; Burgess & Scholer 2015). We know that the necessary coupling and dissipation in space plasmas are usually provided by nonlinear structures, which are often responsible for deviations from the equilibrium. Furthermore, dissipation (quasi-viscosity) could often result from nonlinear structures, owing to wave damping or other processes related to electric currents. Moreover, these nonlinear structures often exhibit (multi-)fractal self-similarity properties at various scales (e.g., Burlaga 1995; Macêk 2006).

Such nonlinear structures essential for turbulence at various scales already have been found in circumplanetary plasma, including the magnetosheath (e.g., Alexandrova 2008; Yordanova et al. 2008). For example, the nature of magnetic fluctuations at ion scales in the solar wind based on Wind (Lion et al. 2016) and Cluster multi-spacecraft missions has been investigated by Roberts et al. (2016) and Perrone et al. (2016, 2017), while in the magnetosheath recent results using very high resolution data on electron scales acquired on board NASA’s Magnetospheric Multiscale (MMS) mission have been presented by Yordanova et al. (2016) and Chasapis et al. (2017). Because the plasma in the magnetosheath is compressible even at a large scale and the bow shock acts as a source of intense fluctuations the conditions are propitious to turbulence in this region (Perri et al. 2009). In addition, using kinetic simulations, Karimabadi et al. (2014) have demonstrated that turbulent processes at shocks could be related to reconnection processes. Obviously, for small scales below the ion gyroradius in the magnetosheath inertial kinetic Alfvén waves may also be active (Chen & Boldyrev 2017). We are aware of the advanced MHD simulations, including Hall effects. But, in spite of this progress, the physical mechanisms of turbulent behavior are still not sufficiently well understood even at the standard inertial range. Therefore, we should still use phenomenological models to describe multiplicative processes, which lead to complex behavior of the plasma.
Since the seminal works of Kolmogorov (1941) and Kraichnan (1965), it is well known that the turbulence in magnetized media should not necessarily be isotropic. In addition, after the past 50 years of investigations, ample evidence exists for various types of anisotropy of solar wind turbulence; for a review, see Oughton et al. (2015). For example, the radial evolution of solar wind intermittency using magnetic field and velocity as measured by Helios in the inner heliosphere for the parallel and transverse components relative to the local magnetic field has been investigated by Bruno et al. (2003), suggesting parallel and perpendicular cascades (Oughton & Matthaeus 2005). The probability density functions of the magnetic field increments beyond the ecliptic plane using Ulysses data have also been obtained by Perri & Balogh (2010). Moreover, it has become evident that to resolve anisotropy in turbulent solar wind flows, the orientation of a scale-dependent local background magnetic field is rather important (e.g., Kiyani et al. 2013; Oughton et al. 2015; Gerick et al. 2017).

This has further stimulated our own studies on properties of turbulence in the magnetosheath depending on shock characteristics using the wealth of data acquired from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission. Admittedly, various space missions provide unique observational data, which allow us to look at phenomena in the space environment. In particular, the THEMIS mission was launched by NASA in 2007 to grasp macroscale phenomena occurring during substorms (Sibeck & Angelopoulos 2008). Moreover, THEMIS data were used for the first time for analysis of turbulence at the terrestrial bow shock (Macek et al. 2015). Namely, we have found that turbulence behind the quasi-perpendicular shock is more intermittent with larger kurtosis than that behind the quasi-parallel shocks.

In this Letter, we extend our study to scale-dependent anisotropic plasma turbulence in the entire magnetosheath, also near the magnetopause, and try to examine how the degree of intermittency depends on the characteristics of the solar and magnetospheric plasmas. We are now concerned with measures of deviations from normal distributions of measured Elsässer-fields in the magnetosheath and in particular, with a comparison between transverse Alfvénic fluctuations and parallel compressive perturbations. Basically, we show that these deviations are often larger for the transverse components, while the parallel fluctuations are close to normal. The data used here are briefly described in Section 2. In Section 3, we show the results of our analysis, suggesting in particular that Alfvénic fluctuations are clearly intermittent mainly in the plane perpendicular to the direction of the local background magnetic field, but along this field for the compressive fluctuations the deviation from the normal Gaussian distribution is rather small. The importance of this intermittent anisotropic turbulent behavior for astrophysical plasmas is underlined in Section 4.

2. Data

We analyze selected time samples acquired between 2008 and 2010 from the THEMIS mission, which consists of five (A–E) space probes (Sibeck & Angelopoulos 2008). In Table 1, we have listed the four chosen time intervals in the magnetosheath (without any sudden nonstationary plasma structures), namely, two samples measured after crossing the bow shock, marked by BS, and two samples obtained before leaving the magnetosheath, i.e., near magnetopause, marked by MP. As discussed before, the directions of the interplanetary magnetic fields in the foreshock and the spectra of the energetic particles in the magnetosheath were helpful for the proper identification of the samples (Macek et al. 2015). The sampling rate here is 3 s, and we consider four long-lasting intervals from 5 to 10 hr. Naturally, the length of each sample depends on the orbit of a particular probe immersed in the magnetosheath during certain periods of time.

It is well known that, in general, dynamics of the shock significantly differs between the quasi-perpendicular and quasi-parallel shocks. Moreover, these shocks themselves also depend on Mach numbers related to the strength of the shock and plasma beta, which is a basic characteristic of the magnetized super-Alfvénic sonic plasma (Kivelson & Russell 1995). The plasma parameter \( \beta \) is the ratio of the thermal pressure \( p \) to the magnetic pressure \( B^2/(2\mu_0\rho) \), where \( \rho = mN \) is the mass density for ions of mass \( m \) and the number density \( N \) (\( \mu_0 \) denotes the permeability of free space). The Alfvén Mach number \( M_A \) is the ratio \( (V/V_A) \) of the ion velocity \( V \) to the Alfvén velocity \( V_A = B/(\mu_0\rho)^{1/2} \), while the magnetosonic Mach number \( M_{ms} \) is the ratio of the velocity to the magnetosonic velocity, \( \nu_{ms} = \sqrt{V_A^2 + V_S^2} \), where the sonic speed is \( V_S = \sqrt{\gamma p/\rho} \) (\( \gamma = 5/3 \) is the polytropic index). Before, we have shown that turbulence just behind the quasi-perpendicular shocks is more intermittent than behind the quasi-parallel shocks (Macek et al. 2015), but its dependence on plasma parameters has not yet been investigated. Therefore, various characteristics of the following parameters in the solar wind are the plasma \( \beta \) and the Alfvén (\( M_A \)) and magnetosonic (\( M_{ms} \)) Mach numbers, which are determined upstream—first, before crossing the bow shock (before entering the magnetosheath) and, next, in the magnetosphere (before crossing the magnetopause), as given in Table 1. A detailed analysis of other samples with various plasma characteristics is presented in a more comprehensive review paper (Macek et al. 2017).

The time profiles of the basic experimental data for two typical clearly quasi-perpendicular cases behind the bow shock, cases (a) and (b), and two other intervals closed to the magnetopause, cases (c) and (d), are shown in Figures 1 and 2, respectively. Here, we show the fluctuations of the plasma ion number density \( N \), the magnitudes of the ion velocity \( V = |V| \), and the magnitude of the magnetic field strength \( B = |B| \) taken from http://cdaweb.gsfc.nasa.gov. We use the Geocentric Solar Ecliptic (GSE) reference system fixed with Earth–Sun line, which is convenient for magnetospheric studies. In this

| No. | THEMIS | Year | Location | Begin | End | \( M_A \) | \( \beta \) | \( M_{ms} \) |
|-----|--------|------|----------|-------|-----|---------|--------|---------|
| (a) | THC    | 2008 | BS       | 10.08.13.45 | 10.08.18.45 | 8.77 | 1.44 | 5.87 |
| (b) | THB    | 2009 | BS       | 06.10.16.45 | 06.11.02.00 | 11.66 | 3.51 | 5.84 |
| (c) | THA    | 2009 | MP       | 12.23.14.00 | 12.23.21.00 | 9.88 | 2.08 | 5.90 |
| (d) | THA    | 2010 | MP       | 12.03.12.45 | 12.03.19.30 | 24.68 | 16.48 | 6.43 |
standard magnetospheric system, the X-axis is positive toward the Sun and the Z-axis is perpendicular to the plane of the Earth’s orbit around the Sun (parallel to the ecliptic pole, positive north); the third direction along the Y-axis in the ecliptic (negative in the direction of planetary motion) completes the right-hand orthogonal GSE system. The regions of the magnetosheath taken for analysis are shaded in Figures 1 and 2. We see that the fluctuations in both regions of the magnetosheath just behind the bow shock as well as near the magnetopause are rather frequent and hence should exhibit substantial intermittent turbulence. However, to obtain a more quantitative measure of intermittency, a detailed analysis is required.

3. Results

We know that turbulence in space plasmas often results in substantial deviations from Gaussian normal distributions. In particular, the fourth moment of the probability density function (kurtosis) is often used as a first indicator of intermittency (e.g., Bruno & Carbone 2013). For any given quantity $x$ with an average $\langle x \rangle$ and standard deviation $\sigma$, we define $\kappa_4 = \frac{1}{N} \sum_{i=1}^{N} [(x_i - \langle x \rangle)/\sigma]^4 - 3$, where $N$ is the number of measurement points. According to this definition, kurtosis $\kappa_4$ is equal to zero for Gaussian distribution. By the way, in turbulence the dependence of statistical moments on spatial scales is often considered. For example, based on spacecraft measurements in the solar wind one can estimate space scales by using the Taylor’s hypothesis (e.g., Macek & Wawrzaszek 2009). In the magnetosheath, the bulk velocity is substantially reduced and this approach could possibly be less valid (e.g., Mangeney et al. 2006; Perri et al. 2017). Therefore, it seems somewhat more appropriate to analyze directly time samples obtained on board several space probes, such as in the case of the THEMIS multi-spacecraft mission. In addition, for a long time, we also know that nonlinear Alfvén waves are present in the solar wind (e.g., Belcher & Davis 1971), possibly associated with discontinuities (Borovsky 2010), current

**Figure 1.** Turbulence near the bow shock (BS).

**Figure 2.** Turbulence near the magnetopause (MP).
sheets, or mirror mode structures resulting from plasma instability (Tsurutani et al. 2011).

The velocity of Alfvén waves according to the well-known formula $V_A = B/(\rho_0 \mu_0)^{1/2}$ can now be obtained using the values of plasma density, velocity, and magnetic field depicted in Figures 1 and 2. In this way, one can calculate the Elsässer (1950) variables, $z^\pm = V \pm V_A$, describing the outgoing and ingoing fluctuations propagating relative to the ambient magnetic field $B_0$. It is worth noting that the sign is taken here relative to the average vector $B_0$. This average surely depends on the timescale $\tau$ responsible for turbulence as recently confirmed by Gerick et al. (2017). Since the time interval during which this average background magnetic field is obtained (say $d\tau$) should be substantially larger than the timescale of turbulence $\tau$, we have used $d = 10$. Having this in mind, similarly to our previous paper on THEMIS data analysis, see Equation (1) of the Macek et al. (2015) paper, the kurtosis of the increments of the various components of both Elsässer vectors $z^\pm$, $z^\pm(t, \tau) = z^\pm(t + \tau) - z^\pm(t)$, is now calculated for a given scale (in units of time resolution).

It is expected that the Alfvénic increments perpendicular to the direction of $B_0$ and the parallel compressive (slow-mode-like) increments should provide rather different contributions to the turbulent behavior of the solar wind plasma (e.g., Bruno et al. 2003; Oughton & Matthaeus 2005). Therefore, we have performed our calculation in the mean field (MF) coordinate system, as described in Appendix D.2 of the review by Bruno & Carbone (2013; see also Bruno & Carbone 2016, Section 3.1). Namely, the direction parallel to the local mean field vector $B_0$ obtained in the GSE system is taken as the $\hat{z}$-axis of the new MF reference system, where the symbol $\hat{z}$ denotes a unitary vector. In this way, the parallel components of both Elsässer vectors $z^+_\parallel$ and $z^-_\parallel$ are calculated. Next, in order to calculate two other components perpendicular to the field $B_0$, $\delta z^+_{\perp 1}$, $\delta z^-_{\perp 1}$ and $\delta z^+_{\perp 2}$, we take for the latter case the axis in the direction perpendicular to the plane containing the mean field $B_0$ and the $X$-axis in the GSE system (but taken here positive outward from the Sun, which is approximately consistent with the radial component of the mean solar wind velocity, $V$), i.e., along $\hat{\mathbf{y}} = B \times \hat{X}$. The remaining transverse components $\delta z^+_\perp$ are along $\hat{\mathbf{x}} = \hat{\mathbf{y}} \times \hat{\mathbf{z}}$ in this plane, which completes the right-handed orthogonal MF system.

The dependence of kurtosis on the timescale $\tau$ for the selected four clearly quasi-perpendicular cases shown in Figures 1 and 2, see Table 1, near the bow shock, cases (a) and (b) in Table 1.

Figure 3. Kurtosis for the increments of the parallel (white circles) and two perpendicular components (black diamonds and squares) of the Elsässer variables, $\delta z^+_{\parallel}$ (left panel) and $\delta z^-_{\parallel}$ (right panel), as a function of timescale $\tau$ near the bow shock, shown in Figure 1, cases (a) and (b) in Table 1.
magnetopause, cases (c) and (d), are depicted in Figures 3 and 4. Here kurtosis for the Elsässer variables is calculated all the way up to $\tau = 100 \, \text{s}$ as compared with the sampling rate of 3 s. We show now the dependence of the parallel and perpendicular components of kurtosis on larger timescales $\tau$ for both the outgoing ($z^+$) and incoming fluctuations ($z^-$). We see that kurtosis near the bow shock, Figure 3, cases (a) and (b) in Table 1, could be smaller ($\beta \sim 1$) than that near the magnetopause, Figure 4, cases (c) and (d) in Table 1. We are aware of limitations to the analysis because of possible instrumental noise: either Poisson noise (from sampling an incomplete velocity distribution function), aliasing, or quantization noise, see, e.g., Appendix of the paper by Chen et al. (2013). However, we are convinced that the influence of any possible noise on the results shown in Figures 3 and 4 could be present mainly at small scales, $\tau \lesssim 25 \, \text{s}$ (after all, if the fluctuations were dominated by Gaussian noise kurtosis would tend to zero).

We can generally notice relatively small differences between $z^+$ and $z^-$, and therefore the outgoing and ingoing fluctuations seem to be roughly similar (except case (b)), which is basically consistent with equipartition of energy suggested by Tu et al. (1989). On the other hand, near the bow shock for small plasma $\beta \sim 1$, when the thermal pressure and the magnetic pressure are similar in the plasma, with moderate Alfvénic Mach number $M_A \approx 9$, Figures 3(a') and (a''), case (a) in Table 1, we have observed only small kurtosis with approximately normal distribution close to equilibrium. For similar $M_A \approx 12$ and somewhat higher plasma $\beta \sim 4$, Figures 3(b') and (b''), case (b) in Table 1, both parallel and perpendicular components of the Elsässer vectors are active. A similar behavior is also observed near the magnetopause, Figures 4(c') and (c''), case (c) in Table 1.

Admittedly, sometimes the parallel components are more important than the perpendicular components, e.g., Figure 3(b''), which is consistent with increasing of the magnitude of the compressive longitudinal magnetic fluctuations as discussed by Alexandrova (2008). A similar behavior has been reported for the magnetic components in the slow solar wind by Bruno et al. (2003, see his Figure 5), but often the opposite holds as for the velocity components in the slow wind (Bruno et al. 2003, Figure 7). One could hence expect that because kurtosis is a proper measure of the level of intermittency its value should depend on the properties of the shocks ($M_A, \beta, M_{\text{ms}}$). A more detailed study of many more samples at various plasma characteristics is given in another comprehensive review paper.
by Macek et al. (2017), supporting the main conclusions of this Letter.

Based on the typical cases presented in this Letter, we can say that both the parallel $\delta z_{\parallel}^{\perp}$ and two perpendicular $\delta z_{\perp 1}^{\perp}$ and $\delta z_{\perp 2}^{\perp}$ components are important, except for the highest value of $M_{A} = 25$ and $\beta = 16.5$. Figures 4(d') and (d''), case (d) in Table 1, where certainly perpendicular $\delta z_{\perp 1}^{\perp}$ components dominate (for $\tau^{+}$ in case (b), Figure 3(b')), it is rather opposite. In addition, it seems that both transverse components are usually different, exhibiting not only anisotropic qualities, but they also seem to be non-gyrotropic with differences in two perpendicular components, which could be due to large-scale shock geometry, the convecting electric field (Narita et al. 2014), or possibly the sampling effect (Turner et al. 2011). For example, in Figure 3(b'') (bottom right) $\delta z_{1}^{\perp}$ and $\delta z_{2}^{\perp}$ are very different and in Figure 4 near the magnetopause all are different, despite having similar shapes (for the bottom two panels (d') and (d'') they still differ by a factor of around 2). Please note that, in this case, the influence of noise could be seen only for very small scales, $\tau \lesssim 10$ s. Therefore, our main conclusions are certainly not affected by noise. Moreover, it is rather clear that for very high Alfvénic Mach numbers and high plasma $\beta$ the Alfvénic waves responsible for turbulence contribute mainly to the transverse components of the Elsässer variables, which is consistent with some previous suggestions (see Belcher & Davis 1971; Oughton & Matthaeus 2005; Perri & Balogh 2010). However, along the magnetic field, the distribution is still close to normal.

4. Conclusions

We have demonstrated that turbulence is intermittent in the magnetosheath in regions near the bow shock and even near the magnetopause. In particular, we have shown that at very high Alfvénic Mach numbers (and high plasma $\beta$), when the thermal pressure dominates the plasma, for the direction along the local background magnetic field the probability distribution of compressive fluctuations should be nearly normal and close to equilibrium with small kurtosis, while in the plane perpendicular to the local magnetic field Alfvénic turbulence resulting from nonlinear interactions is non-gyrotropic with large kurtosis for the Elsässer variables.

On the other hand, intermittency becomes somewhat weaker for moderate $M_{A} \sim 10$ (and $\beta \sim 1$). However, the level of intermittency for the outgoing fluctuations ($\tau^{+}$) seems to be similar to that for the ingoing fluctuations ($\tau^{-}$), which demonstrates equipartition of energy between these oppositely propagating Alfvén waves along the ambient magnetic field.

Admittedly, Wind and Cluster missions have already identified nonlinear structures in the solar wind at ion scales (Lion et al. 2016; Perrone et al. 2016, 2017; Roberts et al. 2016). However, the main goal of the next THOR (Turbulence Heating ObserveR) mission (e.g., Vaivads et al. 2016) is for the first time to have well resolved particle measurements to describe the kinetic scale processes. Hence, in view of the forthcoming space investigations, we expect that our study on the difference in characteristic of intermittency can help to understand better physical processes responsible for turbulence in various regions of space and astrophysical anisotropic plasma.

The research leading to these results has received funding from the THEMIS mission for providing the data, which are available online from http://cdaweb.gsfc.nasa.gov. We would like to thank Roberto Bruno for inspiring discussions and providing us his software for rotating the data into the mean field reference system. This work has been supported by the National Science Center, Poland (NCN), through grant 2014/15/B/ST9/04782.

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