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Key Points:

- Analysis of turbulence using THEMIS data at the terrestrial shocks
- More intermittent turbulence at quasi-perpendicular than quasi-parallel shocks
- Behind quasi-perpendicular shock outward waves are larger than inward waves

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THEMIS observation of intermittent turbulence behind the quasi-parallel and quasi-perpendicular shocks

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Abstract Turbulence is complex behavior that is ubiquitous in nature, but its mechanism is still not sufficiently clear. Therefore, the main aim of this paper is analysis of intermittent turbulence in magnetospheric and solar wind plasmas using a statistical approach based on experimental data acquired from space missions. The quintet spacecraft of Time History of Events and Macroscale Interactions during Substorms (THEMIS) allows us to investigate the details of turbulent plasma parameters behind the collisionless shocks. We investigate both the solar wind and magnetospheric data by using statistical probability distribution functions of Elsässer variables that can reveal the intermittent character of turbulence in space plasma. Our results suggest that turbulence behind the quasi-perpendicular shock is more intermittent with larger kurtosis than that behind the quasi-parallel shocks, which are immersed in a relatively quiet solar wind plasma, as confirmed by Wind measurements. It seems that behind the quasi-perpendicular shock the waves propagating outward from the Sun are larger than possibly damped waves propagating inward. In particular, we hope that this difference in characteristic behavior of the fluctuating space plasma parameters behind both types of shocks can help identify complex plasma structures in the future space missions. We also expect that the results obtained in this paper will be important for general models of turbulence.

1. Introduction

Turbulence is ubiquitous in nature, both in laboratory and space, including the solar wind and planetary magnetospheres. Planetary and solar wind plasmas provide an interesting possibility to look at turbulence in various continuous media in space and astrophysical magnetized plasmas [e.g., *Bruno and Carbone*, 2013]. In fact, recent global fully kinetic simulations of the magnetosphere by *Karimabadi et al.* [2014] show that there is some relation between turbulence near collisionless shocks and magnetic reconnection processes. Admittedly, heliospheric turbulence seems to be intermittent, a point confirmed by its observed fractal and multifractal structures. Therefore, the main aim of our study is to analyze turbulence in magnetospheric plasma using theoretical modeling based on experimental data gathered from space missions.

Notwithstanding progress in MHD simulations of turbulent behavior, including Hall effect, the cause of variability of characteristic magnetofluid parameters is still not fully clear [*Goldstein et al.*, 1995]. Fortunately, the concepts of fractals and multifractals help us to describe multiplicative processes providing a better understanding of the intermittent behavior of various characteristics of plasma [*Frisch*, 1995]. In fact, following basic works by *Kolmogorov* [1941] and *Kraichnan* [1965], various studies have tried to investigate in detail the observed scaling within the framework of multifractal turbulence cascade models that takes into account the distribution of the energy flux between eddies of various sizes [*Meneveau and Sreenivasan*, 1987]. For example, *Marsch et al.* [1996] have analyzed Helios plasma data in circumplanetary space plasma recovering the multifractal scaling of solar wind energy flux in the inner heliosphere. Further, the phenomenological multifractal model has been extended to magnetohydrodynamic turbulence by *Carbone* [1993]. This concept has been first applied for the solar wind magnetized plasma by *Burlaga* [1991], as summarized in his textbook [*Burlaga*, 1995]. Certainly, variability in the solar magnetic fields may also result in scaling. Therefore, the multifractal properties of the magnetic fluctuations have been studied using a wealth of data acquired in the inner heliosphere, for example, by Advanced Composition Explorer (ACE), in the outer heliosphere by Voyager reaching very large distances from the Sun [*Burlaga*, 2004] even at the heliospheric boundaries [*Burlaga et al.*, 2005, 2008, 2013a, 2013b; *Burlaga and Ness*, 2014].

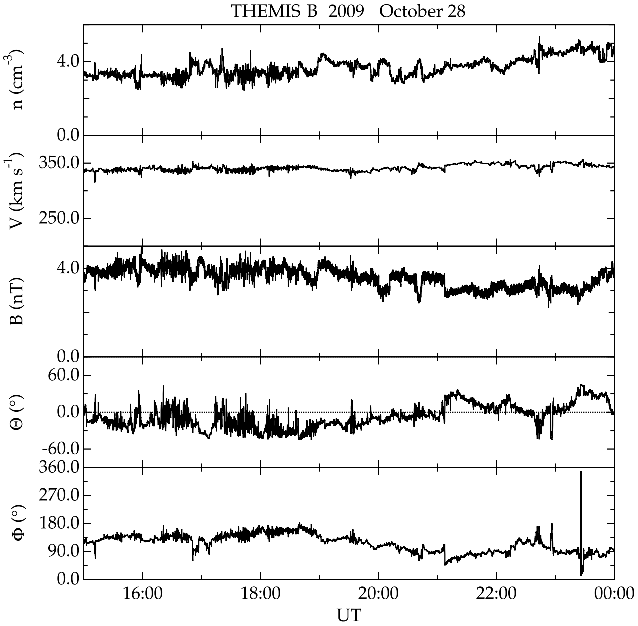

Figure 1. Fluctuations of the plasma density, *n*, plasma velocity, *V*, and magnetic field, *B* (with latitudes Θ and longitudes Φ) observed by THEMIS B spacecraft in the solar wind.

Further, in order to look quantitatively at the scaling of solar wind turbulence, using the partition technique, we have developed a somewhat generalized two-scale weighted Cantor set model that depends on one probability measure parameter and two rescaling parameters [*Macek*, 2007; *Macek and Szczepaniak*, 2008]. Besides the rank-ordered multifractal analysis, the Partition Function Multifractal Analysis is now recognized as one of the modern tools which led to important new information about the multifractal nature of the fluctuations of solar wind turbulence [cf. *Lamy et al.*, 2010; *Chang*, 2015]. Using this methodology, we are able to obtain the generalized dimensions and subsequently the multifractal singularity spectrum. In this way, we have studied the rate of the transfer of the energy flux, where the inhomogeneity of this rate indicates multifractal and consequently intermittent behavior of solar wind turbulence. In particular, we have studied in detail fluctuations of the velocity of the flow of the solar wind, as measured in the inner heliosphere by Helios [*Macek and Szczepaniak*, 2008] and ACE [*Szczepaniak and Macek*, 2008], also at high heliospheric latitudes by Ulysses observations [*Wawrzaszek and Macek*, 2010], in the outer heliosphere by Voyager [*Macek and Wawrzaszek*, 2009], and even at the frontiers of the heliosphere [*Macek et al.*, 2011, 2012, 2014].

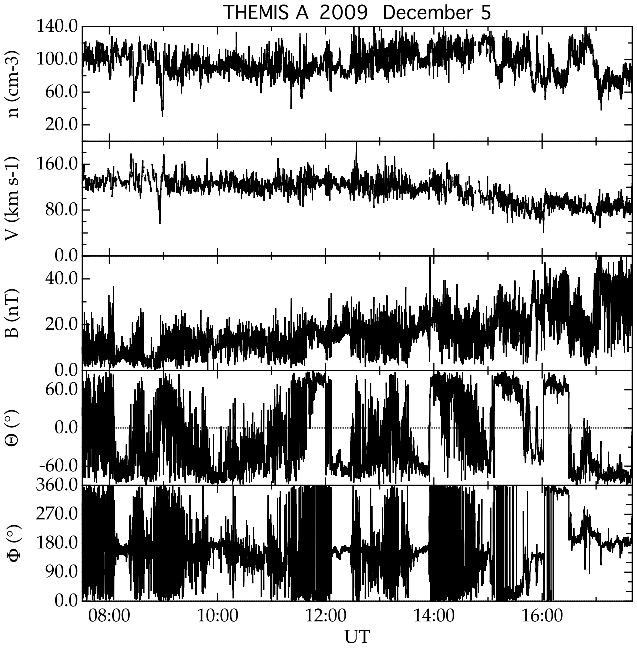

Figure 2. Fluctuations of the plasma density, *n*, plasma velocity, *V*, and magnetic field, *B* (with latitudes Θ and longitudes Φ) observed by THEMIS A spacecraft in the magnetosheath behind the quasi-parallel shock.

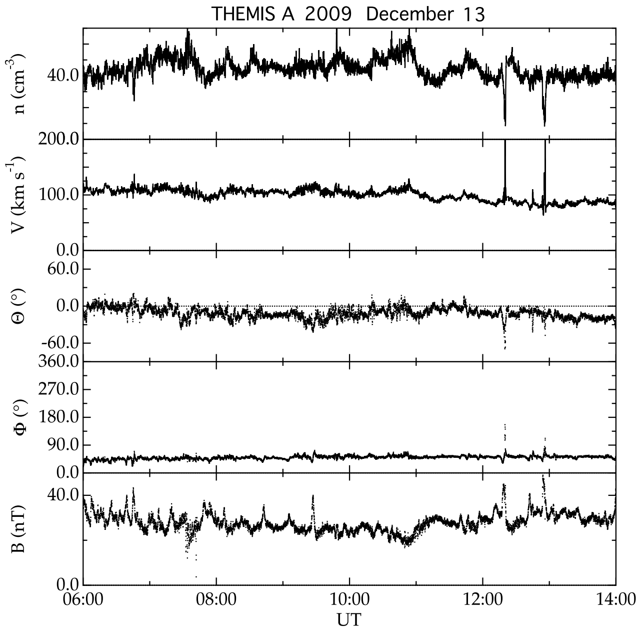

Figure 3. Fluctuations of the plasma density, *n*, plasma velocity, *V*, and magnetic field, *B* (with latitudes Θ and longitudes Φ) observed by THEMIS A spacecraft in the magnetosheath behind the quasi-perpendicular shock.

Admittedly, turbulence near collisionless terrestrial shock has already been studied, including the magnetosheath region [e.g., *Alexandrova*, 2008]. Moreover, magnetosheath plasma turbulence has been observed by Cluster [*Yordanova et al.*, 2008; *He et al.*, 2011], including supermagnetosonic jets reported behind a collisionless quasi-parallel shock [*Hietala et al.*, 2009]. In addition, MHD turbulence has been studied downstream of the quasi-parallel bow shocks of Saturn [*Bavassano Cattaneo et al.*, 2000] and Venus [*Vörös et al.*, 2008]. However, going beyond Cluster, the quintet of Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft allows us to grasp an important difference in turbulent behavior behind planetary collisionless shocks. Therefore, in this paper we analyze characteristics of turbulence at the Earth's shock of various types that basically depend on the direction of the ambient magnetic field. We use higher-order statistics, including skewness and kurtosis, which is a convenient measure of intermittency. Based on the experimental data, our results show that turbulence is more intermittent when the field direction is nearly tangential to the local shock surface. Moreover, we argue that these shocks are immersed in a relatively quiet shocked solar wind plasma. The paper is organized in the following way. In section 2 we review basic characteristics of collisionless terrestrial shocks. The selection of data and methods of analysis are described in sections 3 and 4. Section 5 is devoted to the results of our study. The importance of intermittent behavior of terrestrial plasma for a better understanding of turbulence is underlined in section 6.

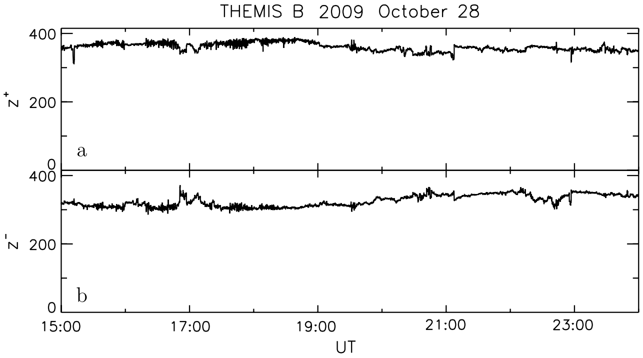

Figure 4. The Elsässer variables, z^+ and z^-, as observed by THEMIS B spacecraft in the solar wind, correspondingly.

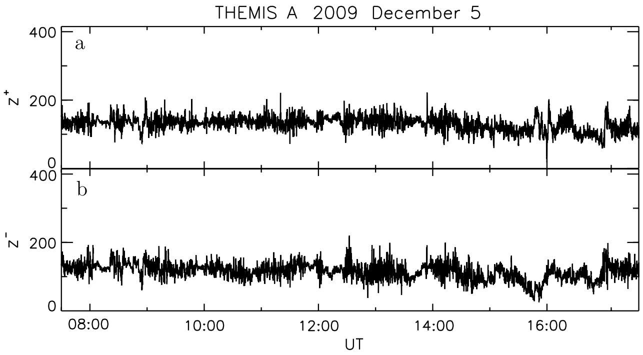

Figure 5. The Elsässer variables, z^+ and z^-, as observed by THEMIS A spacecraft in the magnetosheath behind the quasi-parallel shock, correspondingly.

2. Shock Classification

It is well known that the dynamics of plasma near collisionless shocks depends on the local angle θ between the normal to the shock surface and the direction of the surrounding magnetic field [see, e.g., *Lembege et al.*, 2004]. Therefore, two basic types of planetary shocks are possible, namely, quasi-parallel ($0° \le \theta \le 45°$) and quasi-perpendicular ($45° \le \theta \le 90°$) shocks [e.g., *Leroy*, 1983]. In particular, a radial magnetic field (at the nose of a terrestrial shock) with heliographic latitude $\Theta \sim 0°$ and longitude $\Phi \sim 180°$ corresponds to parallel shock geometry nearly everywhere. However, for a spiral magnetic field with $\Theta \sim 0°$ and $\Phi \sim 135°$ (or 315°), we would have quasi-parallel shock on the prenoon side and a quasi-perpendicular shock on the postnoon side, while the situation is reversed for the spiral with $\Phi \sim 225°$ (or 45°).

3. Data

THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission was launched by NASA in 2007 [*Sibeck and Angelopoulos*, 2008]. From 2007 to 2010 the five spacecraft orbit around the Earth, including three probes, A, D, and E, with apogees that grazed the dayside magnetopause and two others, B and C, on more elliptical orbits with apogees in the solar wind, the magnetosheath, and low latitudes boundary layers. They are all equipped with a full set of plasma and electromagnetic field instruments, including the fluxgate magnetometer and an electrostatic analyzer with ~3 s time resolution [*Auster et al.*, 2008; *McFadden et al.*, 2008]. We obtain the data online from http://cdaweb.gsfc.nasa.gov. Even thought its main objective is to investigate substorms, the multipoint view provided by THEMIS mission has the potential to look at plasma turbulence in the Earth environment.

Admittedly, it is usually a difficult task to copy with nonstationarity. Namely, to identify intermittent turbulence behind the terrestrial shock, we need relatively long samples, where nothing dramatic happens (say there is no change of dynamics of the system). In general, it is hard to distinguish nonlinearity, which causes the shock itself from the nonlinearity resulting in intermittency (possibly related to, e.g., nonlinear Alfvén waves,

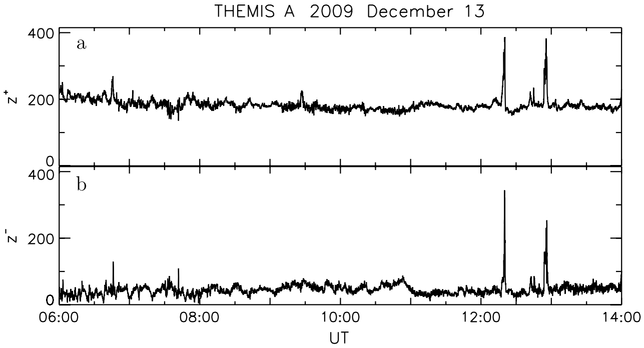

Figure 6. The Elsässer variables, z^+ and z^-, as observed by THEMIS A spacecraft in the magnetosheath behind the quasi-perpendicular shock, correspondingly.

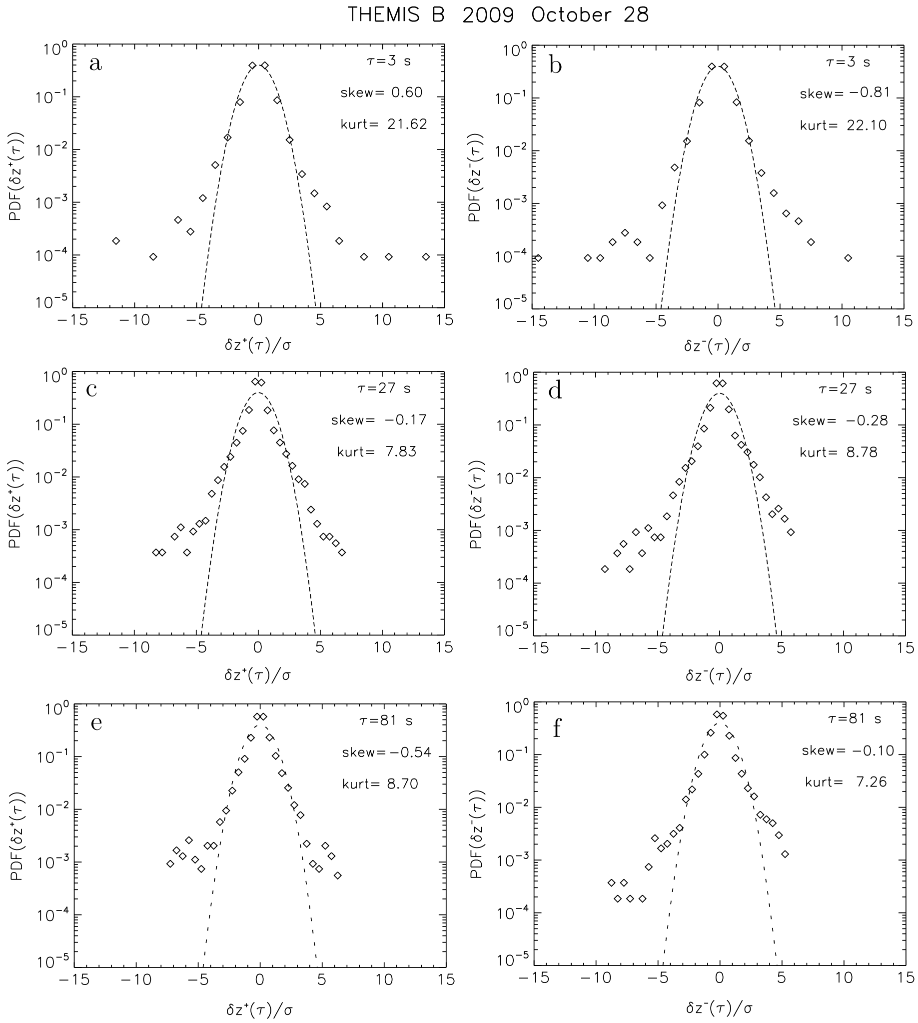

Figure 7. The probability density functions (PDF) of fluctuations of the Elsässer variables, z^+ and z^-, as observed by THEMIS B spacecraft in the solar wind, at scales of $\tau = 3$ s, $\tau = 27$ s, and $\tau = 81$ s, correspondingly, compared with the normal distribution (dashed lines).

coherent structures, and shocklets) as discussed in our earlier papers [e.g., *Macek and Wawrzaszek*, 2013]. Therefore, we have looked for samples where shocks are not present, but admittedly in the chosen samples some brief rapid changes can still appear because those are essential for intermittent dynamics.

Figure 1 shows the basic experimental data: ion number density n, the magnitudes of the ion velocity $V = |\mathbf{V}|$, and the magnetic field strength $B = |\mathbf{B}|$, observed by THEMIS B spacecraft on 28 October 2009 from 15 to 24 UT (in GSE system) located at this period in the solar wind and generally in the foreshock region. Here and elsewhere we have used data with time resolution of 3s. The average Alfvén and magnetosonic Mach numbers are $M_A = 7.3$ and $M_{ms} = 5.4$, respectively. The heliospheric latitudes Θ and longitudes Φ of the magnetic field are also displayed here. In order to look for the properties of turbulence in the vicinity of terrestrial shocks, we have chosen ~10 h of roughly stationary samples with similar parameters observed by THEMIS A spacecraft in the magnetosheath behind the quasi-parallel shock on 5 December 2009 from 0730 to 1738 UT (with upstream values $M_A = 24.9$ and $M_{ms} = 5.3$) and behind the quasi-perpendicular shock on 13 December 2009 from 06 to 14 UT ($M_A = 8.4$ and $M_{ms} = 4.9$) that are shown in Figures 2 and 3, correspondingly. In addition, two samples from Wind when the spacecraft was in the solar wind (with the same time resolution in GSE system) for similar time intervals (on 28 October 2009 from 14 to 24 UT and on 5 December 2009 from 05 to 14 UT) have been taken for comparison.

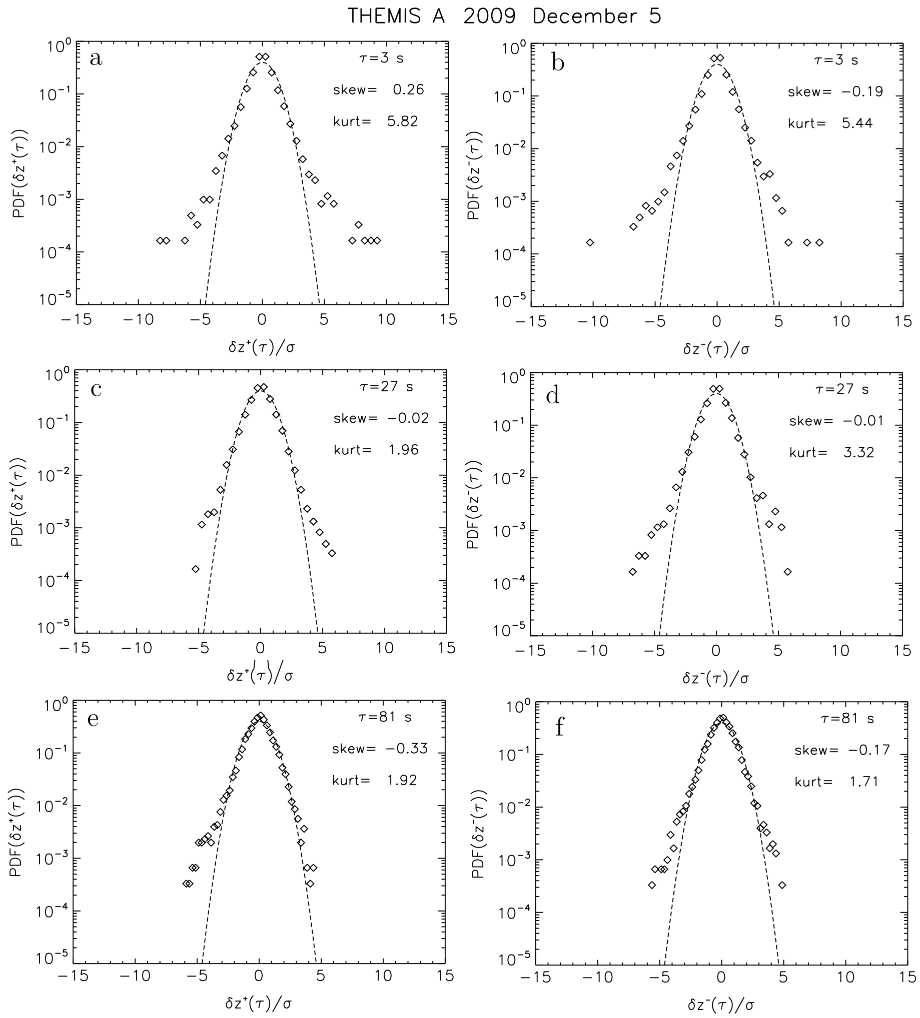

Figure 8. The probability density functions (PDF) of fluctuations of the Elsässer variables, z^+ and z^-, as observed by THEMIS A spacecraft in the magnetosheath behind the quasi-parallel shock, at scales of $\tau = 3$ s, $\tau = 27$ s, and $\tau = 81$ s, correspondingly, compared with the normal distribution (dashed lines).

4. Methods

Basically, intermittent behavior of complex systems often results in non-Gaussian statistics. In particular, the third and fourth moments of the probability distribution function (PDF) of a measured quantity x with average $\langle x \rangle$ and standard deviation σ are given by the skewness and kurtosis, respectively, defined by

$$\kappa_3 = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{x_i - <x>}{\sigma}\right]^3, \kappa_4 = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{x_i - <x>}{\sigma}\right]^4 - 3. \quad (1)$$

Various studies have shown that PDFs of the increments of characteristic parameters describing a turbulent system

$$\delta x(t,\tau) = x(t+\tau) - x(t) \quad (2)$$

at smaller scales τ exhibit a substantial deviation from Gaussianity, resulting especially often in large kurtosis [*Bruno and Carbone*, 2013].

It is also known that turbulence in a neutral fluid is usually described by the Navier-Stokes equations. Moreover, it is known that magnetic fluctuations satisfy the same equations for the Elsässer variables in magnetized plasmas with both bulk and magnetic field-aligned Alfvénic velocities [*Elsasser*, 1950]. This remarkable symmetry suggests that turbulence can occur in hydromagnetic systems coupling the intermittent magnetic field with the motion of the magnetized fluid itself. Therefore, one can expect that hydromagnetic waves in terms of

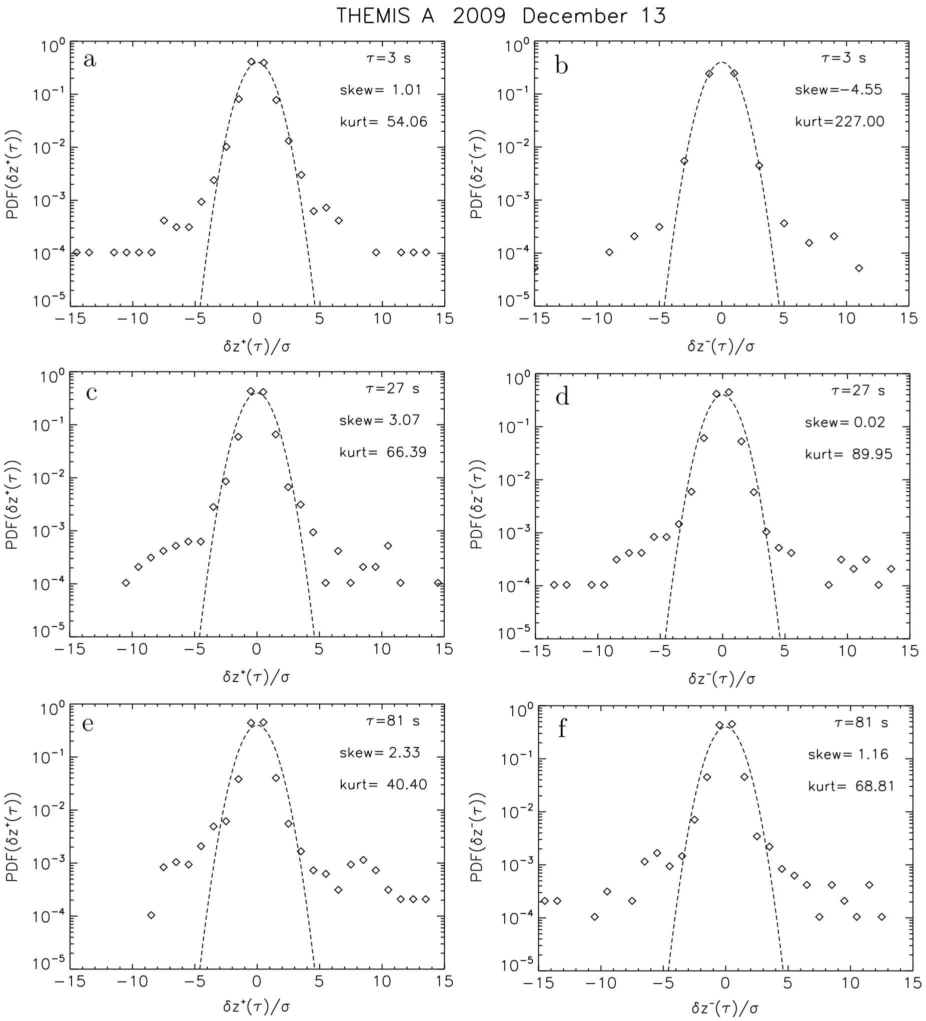

Figure 9. The probability density functions (PDF) of fluctuations of the Elsässer variables, z^+ and z^-, as observed by THEMIS A spacecraft in the magnetosheath behind the quasi-perpendicular shock, at scales of $\tau = 3$ s, $\tau = 27$ s, and $\tau = 81$ s, correspondingly, compared with the normal distribution (dashed lines).

the Elsässer variables are the most suitable for the phenomenological analysis of turbulence in space plasmas with the frozen-in magnetic fields [*Sorriso-Valvo et al.*, 2007].

5. Results

The Alfvénic velocity $\mathbf{v}_A = \mathbf{B}/(\mu_0 \rho)^{1/2}$ can now be calculated from these data: using ion mass m_i or the mass density $\rho = m_i n$ (μ_0 is the permeability of free space). Certainly, this is a characteristic velocity for solar wind turbulence. Therefore, using also the bulk velocity, we need to calculate the Elsässer variables, $\mathbf{z}^{\pm}$, using Alfvénic fluctuations propagating with respect to the direction of the magnetic field [*Roberts et al.*, 1987]. It is convenient to define these variables for waves propagating outward ($\mathbf{z}^+$) and inward ($\mathbf{z}^-$) from the Sun. Therefore, we have $\mathbf{z}^{\pm} = \mathbf{V} \pm \mathbf{v}_A$ for the unperturbed magnetic field $\mathbf{B}_0$ pointing to the Sun and $\mathbf{z}^{\pm} = \mathbf{V} \mp \mathbf{v}_A$ for $\mathbf{B}_0$ pointing away from the Sun, correspondingly [*Bruno and Carbone*, 2013, p. 166].

The results calculated for the magnitudes of both Elsässer variables $z^{\pm} = \sqrt{(z_x^{\pm})^2 + (z_y^{\pm})^2 + (z_z^{\pm})^2}$ are now presented in Figures 4–6, correspondingly. In Figure 4 we see that the fluctuations of these parameters calculated in the solar wind are relatively quiet. However, after crossing the quasi-parallel shock, Figure 5, and the quasi-perpendicular shock, Figure 6, the variations are frequent and rather intermittent, with two prominent peaks corresponding to rapid changes of plasma and magnetic field parameters seen in Figure 3 with brief crossings into the solar wind. One can see that in the solar wind and behind the quasi-parallel shock

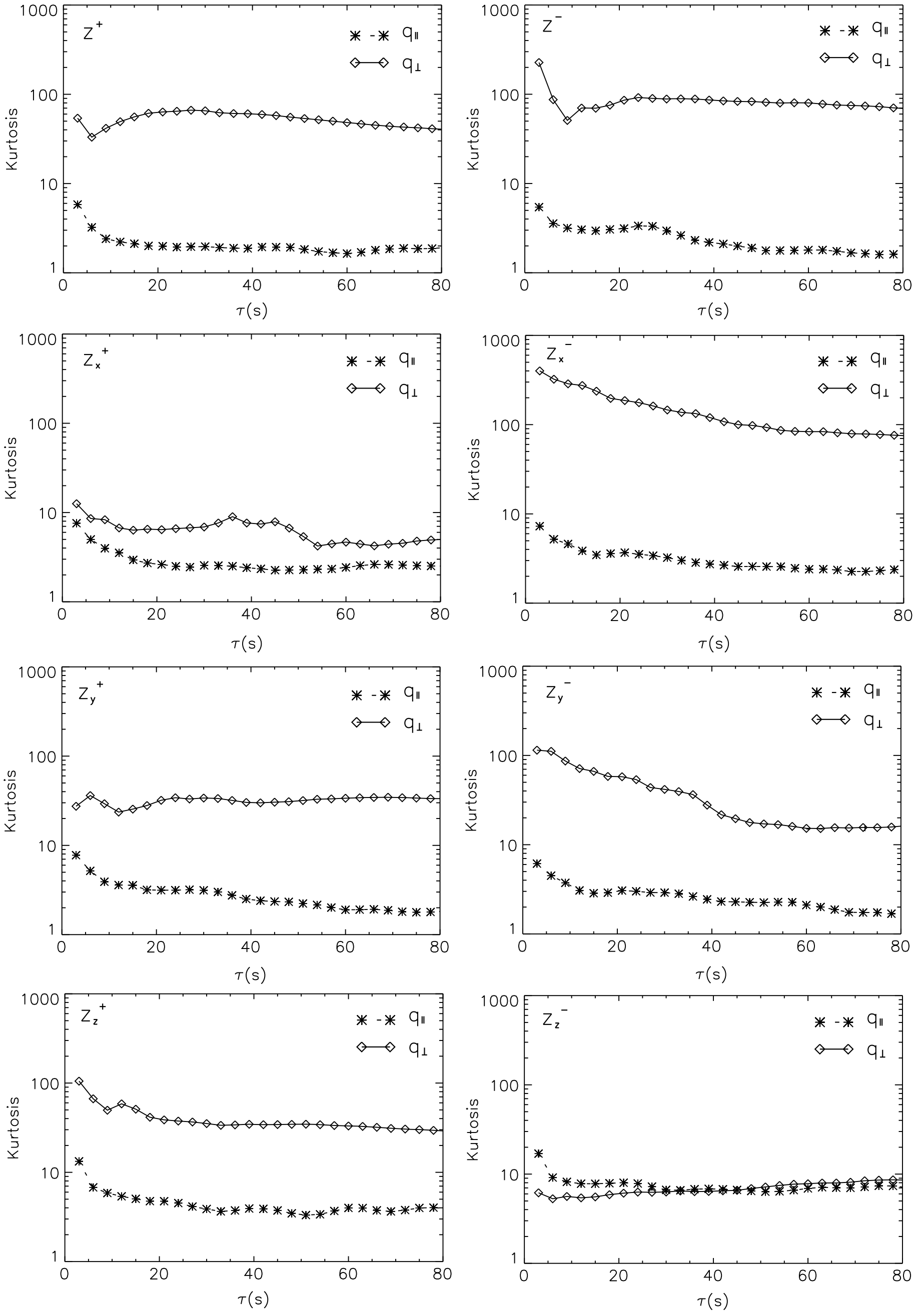

Figure 10. Kurtosis for the magnitude and all components of the Elsässer variables, z^+ and z^-, as a function of time scale τ as observed by THEMIS behind the quasi-parallel ($q_\|$, stars) and quasi-perpendicular ($q_\perp$, diamonds) shocks.

both outward and inward fluctuations are rather similar. However, it is interesting to note that behind the quasi-perpendicular shock the Elsässer variables for waves propagating outward from the Sun (z^+) are larger than that propagating inward (z^-). This means that these inward waves are presumably damped, but certainly identification of the physical mechanism would require further studies.

Next, the probability density functions (PDF) of fluctuations of the Elsässer variables z^+ and z^-, i.e.,

$$\delta z^{\pm}(t,\tau) = z^{\pm}(t+\tau) - z^{\pm}(t), \tag{3}$$

as observed by both THEMIS spacecraft in the solar wind and in the magnetosheath behind the quasi-parallel and quasi-perpendicular shocks, have been calculated for three different scales of $\tau = 3$ s, $\tau = 27$ s, and $\tau = 81$ s, equation (2). The results are displayed in Figures 7–9, correspondingly, with skewness (skew, κ_3, third

Table 1. Kurtosis of the Probability Density Functions (PDF) of Fluctuations of the Elsässer Variables, z^+ and z^-, as Observed by THEMIS (TH) and Wind Spacecraft in the Solar Wind (Foreshock) and in the Magnetosheath (*m* Sheath) Behind the Quasi-Parallel ($q_\parallel$) and Quasi-Perpendicular ($q_\perp$) Shocks at Scales of $\tau = 3$ s, $\tau = 27$ s, and $\tau = 81$ s, Correspondingly

Spacecraft		$\tau = 3$ s		$\tau = 27$ s		$\tau = 81$ s	
Time	Region	z^+	z^-	z^+	z^-	z^+	z^-
TH B 091028	solar wind/foreshock	21.62 ± 0.05	22.10 ± 0.05	7.83 ± 0.05	8.78 ± 0.05	8.70 ± 0.05	7.26 ± 0.05
TH A 091205	*m* sheath $q_\parallel$	5.82 ± 0.04	5.44 ± 0.04	1.96 ± 0.04	3.32 ± 0.04	1.92 ± 0.04	1.71 ± 0.04
TH A 091213	*m* sheath $q_\perp$	54.06 ± 0.05	227.00 ± 0.05	66.39 ± 0.05	89.95 ± 0.05	40.40 ± 0.05	68.81 ± 0.05
Wind 091028	solar wind $q_\perp$ and $q_\parallel$	0.98 ± 0.05	1.15 ± 0.05	0.22 ± 0.05	1.00 ± 0.05	0.22 ± 0.05	1.75 ± 0.05
Wind 091213	solar wind $q_\perp$	0.92 ± 0.05	1.10 ± 0.05	0.53 ± 0.05	1.06 ± 0.05	0.41 ± 0.05	0.81 ± 0.05

moment) and kurtosis (kurt, κ_4, fourth moment) calculated according to equation (1). The actual functions are compared with the normal distributions (dashed lines, with $\kappa_3 = 0$ and $\kappa_4 = 0$). It is important to underline that the deviations from the normal distribution resulting in broader tails with an essential kurtosis are the largest for the case of the quasi-perpendicular shock.

Finally, in order to check as to whether there is actually a difference of intermittency for both types of shocks, in Figure 10 the values of kurtosis for the magnitude z^+ and z^- including all the components of the Elsässer variables are displayed as a function of time scale τ. One can see that generally for larger scales the values of kurtosis are somewhat smaller, which is typical for solar wind turbulence. In particular, for inward waves the main contribution to intermittency comes from the x component along the axis toward the Sun, while for outward waves the fluctuations perpendicular to this axis are important. We also observe a saturation of this fourth moment of the distribution functions.

Hence, we can argue that turbulence behind the quasi-perpendicular shock is more intermittent with larger kurtosis, equation (1), than that behind the quasi-parallel shocks. Even though the overshoot at the former case is more dramatic than in the latter case, such a change of character of turbulence behind the shock was not expected. Admittedly, it is difficult to see this difference of behavior in Figures 5 and 6. However, by comparing Figures 8 and 9, one can verify that behind the quasi-perpendicular shock numerous (apparently non-self-similar) tiny fluctuations contribute to a fatter tail. In fact, kurtosis that is fourth moment of non-Gaussian probability distributions is also the deviation from self-similarity and is, hence, a measure of intermittency [*Frisch*, 1995]. Moreover, the plasma in the foreshock filled up with the subsonic solar wind is relatively quiet resulting in a substantially smaller kurtosis.

All the characteristic parameters as observed by THEMIS spacecraft in three distinct regions of the circum-terrestrial plasma, namely in the solar wind (foreshock) and in the magnetosheath (*m* sheath) behind the quasi-parallel ($q_\parallel$) shock and behind the quasi-perpendicular ($q_\perp$) shock, are summarized in Table 1, which includes also some solar wind data detected by Wind. These additional data confirm that the solar wind plasma has roughly normal distribution. The values of kurtosis of the probability density functions (PDF) obtained for fluctuations of all x, y, and z components of the Elsässer variables, z^+ and z^-, in GSE system as observed by THEMIS spacecraft in the respective regions of Table 1 (at scales of $\tau = 3$ s) are also specified in Table 2. We see that the largest kurtosis corresponds to fluctuations behind the quasi-perpendicular shock propagating along the Earth-Sun line inward, z_x^-, with somewhat smaller outward fluctuations z_z^+ along the direction of the ecliptic North Pole.

Table 2. Kurtosis of the Probability Density Functions (PDF) of Fluctuations of x, y, and z Components of the Elsässer Variables, z^+ and z^-, in GSE System as Observed by THEMIS Spacecraft in the Solar Wind (Foreshock) and in the Magnetosheath (*m* Sheath) Behind the Quasi-Parallel ($q_\parallel$) and Quasi-Perpendicular ($q_\perp$) Shocks at Scales of $\tau = 3$ s

Spacecraft, Time	z_x^+	z_y^+	z_z^+	z_x^-	z_y^-	z_z^-
TH B 091028	21.51 ± 0.05	1.36 ± 0.05	29.05 ± 0.05	24.32 ± 0.05	1.84 ± 0.05	45.96 ± 0.05
TH A 091205	7.59 ± 0.04	7.76 ± 0.05	13.27 ± 0.04	7.28 ± 0.04	6.14 ± 0.04	16.98 ± 0.04
TH A 091213	12.57 ± 0.05	27.43 ± 0.05	105.15 ± 0.05	400.31 ± 0.05	114.56 ± 0.05	6.17 ± 0.05

6. Conclusions

We have analyzed plasma and magnetic field experimental data gathered onboard THEMIS quintet spacecraft looking for basic characteristics of intermittent turbulence near the terrestrial shock.

It seems that turbulence behind the quasi-perpendicular shock is more intermittent with larger kurtosis than behind the quasi-parallel shock. Moreover, in the former case the waves propagating outward are larger than that propagating inward from the Sun, which are possibly damped, while in the latter case both amplitudes of Elsässer variables are rather similar. In addition, both types of terrestrial shocks are immersed in a relatively quiet less intermittent solar wind plasma.

We therefore hope that this difference in characteristic behavior of the fluctuating space plasma parameters behind both types of shocks can help identify complex plasma structures in the future space missions. For example, because the determination of shock normal is rather difficult in practice, the values of kurtosis of the probability distribution functions can be useful to indicate whether the spacecraft crossed the quasi-perpendicular or quasi-parallel shock.

We also expect that the results obtained in this paper will be important for general models of turbulence. We therefore hope that they will contribute to a better understanding of the nature of turbulence, which is still a challenging unresolved issue in contemporary science.

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