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EVOLUTION OF ION-SCALE TURBULENCE DURING PLASMA CROSSING OF THE EARTH'S BOW SHOCK

L. Rakhmanova, M. Riazantseva, G. Zastenker, Yu. Yermolaev, I. Lodkina

Space Research Institute of Russian Academy of Sciences, Moscow, Russia

Abstract. We present a case study of modification of turbulent cascade at ion scales during plasma crossing of the Earth's bow shock. We analyze ion flux measurements with 31 ms cadence provided by the BMSW instrument onboard the Spektr-R satellite. Changes in shape and characteristics of Fourier spectra of ion flux fluctuations are considered for three cases of the bow shock crossing. Deviation of spectra from typical shape is shown just behind the bow shock. Also, influence of the large-scale solar wind type on the evolution of turbulent cascade during the bow shock crossings is analyzed statistically.

1. Introduction

Magnetosheath (MSH) transfers any disturbance taking place in the solar wind (SW) toward the Earth's magnetosphere. Both SW and MSH plasmas were shown to be turbulent. Turbulence in these regions has been examined for several decades (e.g. *Bruno & Carbone*, 2013; *Alexandrova et al.*, 2013). Generally, turbulent cascade is assumed to be formed by incompressive alfvenic fluctuations at MHD scales (larger than proton gyroradius ρ_{ci}) which transform to compressive kinetic alfven waves at smaller (kinetic) scales (e.g. Schekochihin et al., 2009). Most of the studies were focused on magnetic field fluctuations. However, recent statistical studies reveal that MSH turbulence may be dominant by compressive fluctuations, which do not correspond to alfvenic nature (e.g. *Huang et al.*, 2017). Fluctuations of plasma parameters worth to be analyzed as well in order to find out which type of fluctuations forms the turbulent cascade and determines processes leading to energy dissipation in collisionless plasma.

Before year 2011 low time resolution of plasma measurements made it difficult to prepare reliable analysis of ion scale plasma fluctuations. Since the Spektr-R launch in 2011 with the Bright Monitor of Solar Wind (BMSW) instrument on board the comprehensive statistical studies of plasma fluctuations at ion and sub-ion scales have been presented in the SW (*Riazantseva et al.,* 2015; *Šafránková et al.,* 2015, 2016) as well as in the MSH (*Rakhmanova et al.*, 2016, 2018a,b). These studies provide typical shape and characteristics of spectra of plasma parameters' fluctuations. Also, statistics provides an evidence of modification of turbulent cascade at the Earth's bow shock.

According to *Rakhmanova et al.* (2018a,b) in the MSH close to the bow shock the spectra of ion flux fluctuations are flatter at MHD scales and steeper at kinetic scales compared to those observed in the undisturbed SW and predicted by most of the theories (see review by *Alexandrova et al.*, 2013). Authors demonstrated evolution and recovery of the turbulent cascade towards the magnetopause as well. Also, changes in turbulent spectra were reported for magnetic field fluctuations. *Czaykowska et al.* (2001) performed statistical study of changes of magnetic field fluctuation spectra during subsolar bow shock crossings. Authors showed flattening of spectra at MHD scales, with power exponents of the approximation functions being of the order of -1 behind the bow shock. *Huang et al.* (2017) analyzed evolution of magnetic field fluctuation spectra across the MSH with the help of extensive statistics of Cluster measurements throughout the subsolar MSH. The authors also showed ~f^{-1} spectra at MHD scales just behind the bow shock and their steepening up to -5/3 toward the magnetopause. Steepening of spectra at the kinetic scale was mentioned in the vicinity of the bow shock as well.

However, statistical analysis cannot consider the upstream conditions in the SW for each of the observed spectra in the MSH. Present paper focuses on a case study to take into account the influence of the state of the turbulence in front of the bow shock on the features of the cascade in the MSH.

2. Observations

Current study deals with BMSW (*Zastenker et al.*, 2013, *Šafránková et al.*, 2013) instrument measurements of the ion flux value with 31 ms time resolution. Also, proton density and bulk velocity data from BMSW with time resolution 3 s were used. Fig. 1 presents time series of ion flux (*a*), ion density (*b*) and bulk velocity (*c*) measurements on November 24, 2012. Spektr-R moved from the SW, crossed the bow shock three times at 16:20, 17:00 and 17:13 UT and then stayed in the MSH. Spacecraft location was {-6; -19; -24} R_E in Geocentric Solar Ecliptic coordinate system. Shaded areas in panel *a* mark two regions distinguished for further analysis.

Fourier spectra of ion flux fluctuations were considered in order to analyze features of the turbulence. Spectra were calculated with the help of fast Fourier transform with subsequent smoothing in frequency frame. Calculations were prepared for intervals of 35 minutes durations which corresponded to ~65000 data points in each spectrum. Before calculations ion flux fluctuations were normalized to the mean value over the interval. Obtained spectra are presented in Fig. 1d. Grey line refers to the upstream region (i.e. SW) while black line corresponds to the region downstream of the bow shock (MSH). In the SW the ion flux (or density) fluctuation spectra can be approximated by three power laws: frequency range [0.01-0.2] Hz corresponds to MHD scales while at ~3 Hz the spectral break occurs with steeper spectrum at higher frequencies (kinetic scales). In the intermediate frequencies one can see flattening of the spectrum, which are supposed to be due to the contribution of the kinetic alfven waves (see *Chandran et al.*, 2009). In the MSH the spectrum can be approximated by two power-law functions separated by break and superimposed with the bump at 0.4 Hz. Similar bumps usually occur in the spectra obtained in the vicinity of the bow shock and are supposed to be due to instabilities arising in this region (*Schwartz et al.*, 1996).

Obtained spectra are typical for both regions (e.g. *Riazantseva et al.,* 2015; *Šafránková et al.,* 2015; Rakhmanova et al., 2018a). In the SW the slope (power exponent) of the spectrum at MHD scales equals to -1.89±0.03. This value does not correspond well to Kolmogorov's spectrum with slope of -5/3 which is predicted usually in theories of developed turbulence (*Frisch*, 1995). However, this value of spectral slope is often observed in the SW (see *Riazantseva et al.*, 2015). Behind the bow shock the MHD part of the spectrum at Fig. 1*d* is significantly flatter with -1.3 slope. At kinetic scales upstream as well as downstream spectra have slope -3.2.

In present paper two more crossings were considered. Table 1 presents slopes of the spectra upstream and downstream of the bow shock at MHD scales S_1 and at kinetic scales S_2 together with spacecraft locations during three analyzed events. All three crossings took place for quasi-perpendicular bow shock at the flank MSH. For two of three cases significant flattening of the MHD part of spectra occurs behind the bow shock. For the last case (March 26, 2017) spectrum flattens slightly in the MSH. Values of spectral slopes S_1 in the MSH corresponds well to the statistical distributions, obtained in (*Rakhmanova et al.*, 2018b).

At kinetic scales steepening of spectra just behind the bow shock occurs in two of three cases. In the case used as the example in Fig. 1 no steepening of spectrum can be observed. Note that spectral slopes, obtained for other two cases (February 28, 2015 and March 26, 2017) are untypical for the MSH plasma (*Rakhmanova et al.*, 2018a). Never mind, significant steepening of the spectra takes place for these crossings

As it was mentioned in the Introduction, magnetic field fluctuation spectra were shown to be modified behind the bow shock also (*Czaykowska et al.*, 2001; *Huang et al.*, 2017). Present study qualitatively correspond to the reported results. However, BMSW measurements do not provide evidence for constant presence of spectral slope close to -1 at MHD scales behind the bow shock. This difference may be due to considering flank MSH instead of subsolar region where plasma is highly disturbed. However, flattening of ion flux fluctuation spectra is the evidence of redistribution of energy in the turbulent cascade due to the interaction with the bow shock at all parts of the MSH.

At the kinetic scales both magnetic field (*Huang et al.*, 2017) and plasma (*Rakhmanova et al.,* 2018a) fluctuation spectra behind the bow shock were shown to be steeper than those observed in the SW and predicted by theories. However, this result was obtained statistically. Present study reveals values of spectral slopes that differs from the results of the statistical analysis. However, for these cases upstream plasma was characterized by non-typical spectral slopes as well and steepening of the spectra occurred behind the bow shock for the most of the cases. That is, interaction with the bow shock leads to increase of the dissipation rate while the mechanisms of dissipation are governed by local parameters of plasma.

In recent paper by *Pitňa et al.* (2016) authors analyzed influence of the interplanetary shock on the turbulent cascade at the scales of transition from MHD to kinetic regimes.

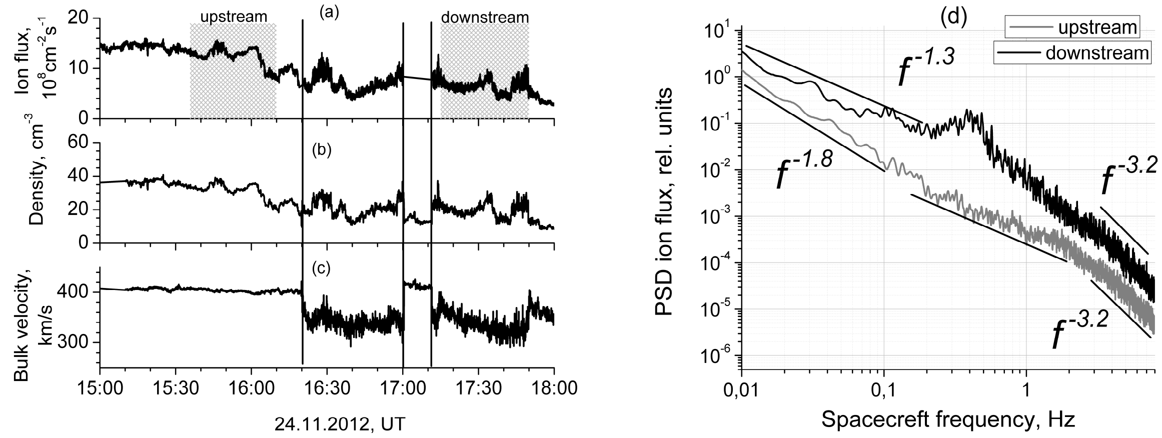

Figure 1. Time series of (***a***) ion flux, (***b***) density and (***c***) bulk velocity measurements on board Spektr-R satellite on November 24, 2012; (***d***) ion flux fluctuation spectra upstream (grey) and downstream (black) of the bow shock (calculated for the shaded intervals in panel *a*).

Table 1

Date	S_1		S_2		GSE position, R_E			SW type
	SW	MSH	SW	MSH	X	Y	Z	
24.11.2012	-1.89±0.03	-1.30±0.04	-3.22±0.02	-3.21±0.03	-6	-19	-24	MC
28.02.2015	-1.81±0.04	-0.96±0.06	-1.89±0.02	-2.2±0.01	-22	28	-20	SHEATH
26.03.2017	-1.58±0.09	-1.53±0.03	-2.02±0.02	-2.4±0.01	-20	29	-13	SLOW

Spectra slopes at kinetic scales S_2 at upstream and downstream regions were shown to be linearly connected though steepening of the spectrum occurred after the interplanetary shock passage. At MHD scales the spectral slopes S_1 in the upstream and downstream regions were also linearly connected. However, turbulence in the downstream region were characterized by $S_1 \sim -5/3$ typically (*Pitňa et al.*, 2017). Thus, turbulent cascade changes in different way during crossings of interplanetary shock or Earth's bow shock. Redistribution of energy in turbulent cascade leading to deviation of spectrum from the Kolmogorov-like scaling seems to be inherent for plasma behind the Earth's bow shock.

3. Magnetosheath turbulence affected by solar wind streams of different type

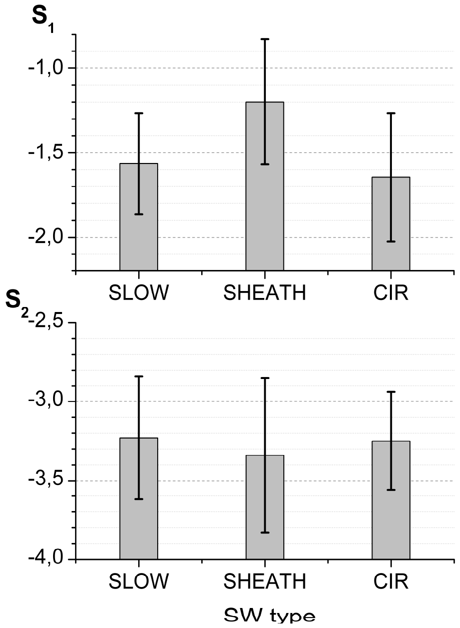

Figure 2. Dependence of the spectral slopes S_1 (*top panel*) and S_2 (*bottom panel*) behind the bow shock on large-scale SW type.

The SW streams are known to have different properties depending on its origin at the Sun. Several large-scale types of the SW can be distinguished. In present paper classification by *Yermolaev et al.* (2009) was used in order to find out influence of the large-scale type of upstream SW on the characteristics of turbulence downstream of the bow shock. For this purpose, the spectra obtained in the MSH in the vicinity of the bow shock were chosen from the statistics presented in (*Rakhmanova et al.*, 2018b). For each of the spectra upstream SW type was determined together with mean values of spectral slopes S_1 and S_2 at MHD and kinetic scales, respectively. Fig. 2 presents dependencies of S_1 (top panel) and S_2 (bottom panel) on the selected types of the SW: SLOW - undisturbed solar wind stream (210 spectra), SHEATH - compressed region before interplanetary coronal mass ejection regions (85 spectra), and CIR - corotating interaction regions - compressed region before fast solar wind stream (62 spectra). Other types of the SW were too rare in the considered data set to use it for statistical analysis. As to kinetic scales, no relation can be found between the SW type and spectral slope S_2. This fact confirms the suggestion of local character of dissipation at kinetic scales in the MSH. On the other hand in spite of large spread of values (represented by error bars in Fig. 2) one can see that MHD part of turbulent cascade associated with the SW of type SHEATH undergoes the most significant changes at the bow shock: $S_1^{Sheath} = -1.2\pm0.3$ while for the SW of types SLOW and CIR spectra at MHD scales have slopes $S_1^{Slow,\ CIR} = -1.6\pm0.3$ behind the bow shock. Also, the SW types are listed in last column of Table 1 for each of the case studies presented in previous section. One can see that statistical results correspond well to the results of the case study. Case study observed during the SW of type SHEATH is characterized by the most significant changes in turbulent spectrum during the bow shock crossing, while the change is insignificant for crossing which take place during SW of type SLOW. Also, moderate changes in the spectrum occurred for November 24, 2012 when the SW of type Magnetic Cloud (MC) took place. However, this type of SW was not included in the statistical study in current section.

4. Results

Case study of three bow shock crossings by the Spektr-R satellite have been prepared. Analysis of spectra of ion flux fluctuations at frequencies which correspond to transition from MHD to kinetic scales reveals following:

1) flattening of MHD part of spectra occurs in the most of the cases behind the bow shock regardless the slope of the spectra in the upstream region;
2) at kinetic scales steepening of the spectra is usually observed;
3) the most significant changes in the MHD part of spectra occur during the SW of type SHEATH while during SLOW SW the turbulent cascade undergoes insignificant changes at the bow shock.

Obtained results correspond well to the results of statistical studies prepared both for magnetic field (*Huang et al.*, 2017) and plasma (*Rakhmanova et al.*, 2018a,b) fluctuations. However, case study helps to compare direct changes in the cascade. That is, redistribution of energy takes place at the bow shock that leads to deviation of spectra from the shape predicted in theories of developed turbulence. Crossing of the bow shock results in increase of the dissipation rate, though mechanism of dissipation is governed by the local plasma parameters and depend on upstream conditions in the SW. Moreover, comparison between changes of the turbulent cascade during bow shock crossing and during interplanetary shock propagation reveals differences in the turbulence characteristics in the downstream regions. That is, deviation of the spectral shape from the predictions of the theories of developed turbulence is likely to be inherent feature of plasma in the region behind the Earth's bow shock.

Characteristics of turbulence change at the bow shock, and its modification differs for various conditions in the upstream SW. As the MSH serves as a link between the SW and the magnetosphere, obtained results should be taken into account for development of models of Sun-Earth relations.

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