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PROPERTIES OF THE MAGNETOSHEATH PLASMA TURBULENCE UPSTREAM AND DOWNSTREAM INTERPLANETARY SHOCKS

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Abstract. We present a case study of small-scale plasma fluctuations affected by the interplanetary shock in the Earth's magnetosheath. The study concentrates the kinetic scales - scales of the order of ion gyroradius. Features of the ion flux fluctuation spectra are considered upstream and downstream the interplanetary shock registered on board the Spektr-R spacecraft in the flank magnetosheath. Present analysis indicates differences between plasma turbulence influenced by interplanetary shocks in the solar wind and in the magnetosheath. Moreover, interplanetary shocks are shown not to change the level of the ion flow intermittency in the magnetosheath.

1. Introduction

Magnetosheath plasma is known o be turbulent (e.g. *Lacombe et al.*, 2006; *Mangeney et al*., 2006; *Alexandrova et al*., 2008). To date magnetosheath turbulence is well discussed from MHD to electron scales with the help of magnetic field data (see e.g. *Alexandrova et al.*, 2008, *Huang et al*., 2014 and references therein). Recently statistical studies of the kinetic-scale (scales around ion giroradius) turbulence features in the magnetosheath with the help of plasma measurements was presented also (*Riazantseva et al*., 2016; *Rakhmanova et al*., 2016).

Developed turbulent cascade in the near-Earth plasma is believed to have several scales including injection range exhibiting power law with spectral slope ~-1, inertial range exhibiting power law with spectral slope -5/3 and the range of dissipation with steeper spectra (see review by *Bruno and Carbone*, 2013). Large-scale plasma structures such as interplanetary shocks may contribute to the cascade formation and provide an interesting examples of turbulence dynamics. Plasma turbulence in the solar wind affected by the interplanetary (IP) shocks was studied by (*Pitňa et al*., 2016). Authors considered several tens of IP shocks in the solar wind and found out follows: 1) power spectral density of the ion flux fluctuations increased by a factor of 10 downstream fast forward IP shocks; 2) spectral indices downstream the IP shocks are proportional to those upstream the IP shocks; 3) in half of the cases kinetic-scale part of the spectra turned to have exponential cut-off instead of power law spectra downstream the IP shocks.

Present study deals with magnetosheath plasma turbulence affected by the IP shocks. We consider several case studies of the IP shock propagation through the magnetosheath and compare Fourier spectra upstream and downstream the shock. Also we present an analysis of ion flow intermittency level upstream and downstream the shock front.

2. Observations

We use BMSW (Fast Solar Wind Monitor) instrument (*Zastenker et al*., 2013; *Šafránková et al*., 2013) data on board Russian Spektr-R spacecraft. The instrument measures ion flux value and direction and, in some cases, proton density, bulk and thermal velocity with a time resolution 31 ms. This time resolution is enough to study turbulent cascade at scales of transition between inertial and dissipation ranges. In the current study we use ion flux value measurements for this data is continually available from Spektr-R. The ion flux variations represent mostly the fluctuations of ion density (see e.g. *Pitňa et al*., 2016).

Fig. 1 shows the example of IP shock registered in the magnetosheath on December 19, 2015 at 16:26. Panels *a-c* present ion flux value, number density and bulk velocity respectively from Spektr-R (black lines). Grey lines presents solar wind data from Themis-C spacecraft, shifted to match the shock fronts. Spektr-R is located at {-41; -25; 13} R_E in GSE coordinate system; Themis-C is located at {-16; 54; -1} R_E in the solar wind. The IP shock speed is V_{IP} = 525 km/s, the angle between magnetic field direction and the shock normal is $\theta_{BN}^{IP}=55^0$. The IP shock characteristics were calculated using multispacecraft technique in the solar wind (*Song and Russel*, 1999).

In order to study influence of the IP shock on the kinetic-scale plasma turbulence we consider Fourier spectra calculated on ~17 min time intervals. This time intervals corresponds to ~0.01-10 Hz in frequency domain. Typically, ion flux spectra in the magnetosheath in this frequency range are described by two power laws with break between them. *Rakhmanova et al*., (2016) showed spectral indices to be S_1=1.8±0.2, S_2=2.9±0.3 and F_{BREAK}=0.8±0.5 Hz, where S_1 and S_2 are the slopes of the first and the second power law parts respectively, and F_{BREAK} is the frequency at which the break between two power law parts is observed.

Shadowed areas in Fig. 1 show time intervals used for spectra calculations foe the analyzed case. These intervals are shifted from the front by several minutes to avoid an influence of wave phenomena associated with the shock front. Fig. 2 presents the frequency spectra upstream (black line) and downstream (grey line) the IP shock on December 19, 2015. Spectra are approximated with two power laws and break. The spectral indices are shown in the figure. One can see that spectral power increases by the factor of 40 downstream the IP shock. This value is comparable by the order of magnitude with the results of (*Pitňa et al.*, 2016) in the solar wind. Spectral slope S_1 is close to

Kolmogorov's predictions of -5/3 (*Kolmogorov*, 1941) both downstream and upstream the IP shock. We do not consider this slope further for we deal with kinetic scale turbulence. Spectral slope S_2 is nearly the same upstream and downstream the shock front and is close to -2.6. The break frequency F_{BREAK} increases from 0.75 Hz upstream to 2.07 Hz downstream the front. Such increase can be due to the changes of plasma and magnetic field parameters at the front, that is, characteristic frequencies which are supposed to be responsible for the break position are different upstream and downstream the front. As it was mentioned above, in the solar wind *Pitňa et al.*, (2016) showed exponential cutoff of the spectrum downstream the shock front in ~50% of cases. The spectrum at Fig. 2 does not exhibit exponential cutoff.

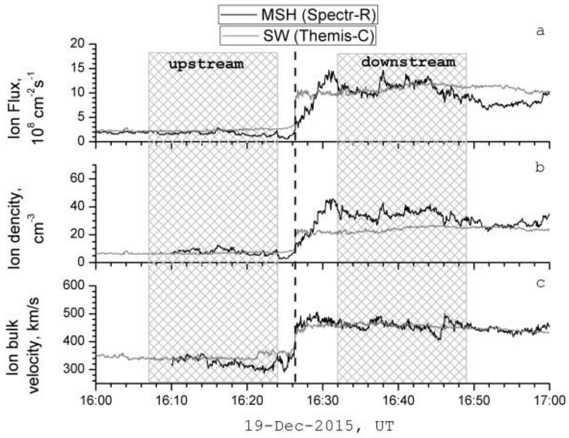

Figure 1. Interplanetary shock registered in the magnetosheath by Spektr-R spacecraft on December 19, 2015. Black line presents Spectr-R measurements in the magnetosheath, grey line presents Themis-C measurements in the solar wind shifted to match the shock fronts. Intervals used for spectra calculations are shaded.

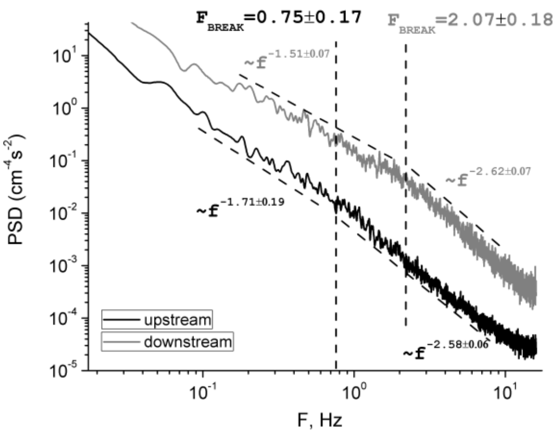

Figure 2. Fourier spectra calculated on 17-min intervals upstream (black line) and downstream (grey line) the interplanetary shock on December 19, 2015. Spectral indices are shown in the figure.

We have managed to collect four cases of IP shock registration in the magnetosheath by Spektr-R spacecraft. All of the cases are observed behind the quasi-perpendicular bow shock. However, two of them are accompanied by the bow shock crossing in several minutes after IP shock registration. For this reason we cannot calculate reliably spectral indices S_1 and F_{BREAK} for the lack of data points number. However, the slope S_2 can be calculated. For this reason in the further study we deal only with slope S_2 and power spectral density (PSD) of the spectra. The characteristic of the shocks and spectra parameters for all of the cases are shown in Table 1. Bolded rows in the table present cases when 17 min time intervals are available upstream as well as downstream the IP shock. In other cases 4 min time intervals are used.

Table 1.

IP shock registration date	IP shock characteristics		Spectral slope S_2		$PSD^{downstream}/PSD^{upstream}$
	Speed, km/s	θ_{BN}^{IP}, ^{0}	upstream	downstream	
15-Mar-2013	**460**	**64**	**-1.9**	**-2.0**	**20**
19-Dec-2015	**525**	**55**	**-2.5**	**-2.4**	**40**
08-Oct-2013	475	54	-2.2	-2.8	60
27-Feb-2014	375	81	-3.2	-2.0	250

Comparing rows in Table 1 one can conclude that: 1) all of the IP shocks are quasi-perpendicular - $\theta_{BN}^{IP}>45^0$; 2) in two cases of four spectral slope S_2 does not change across the shock front, while in other cases both steepening and flattening of the spectra occur downstream the shock front; 3) for three cases PSD increases by the order of amplitude downstream the IP shock, while in one case (February 27, 2014) it increases by a factor of 250. In this case the θ_{BN}^{IP} angle is the largest and the shock speed is the smallest comparing to other cases.

Turbulence in the space plasma is known to be intermittent (*Bruno and Carbone*, 2013). Intermittency results in deviation of the probability distribution function (PDF) from the Gauss distribution with decreasing of scale. Intermittency level can be estimated by the deviation of flatness coefficient – 4-th order moment of the PDF – from the flatness coefficient of the Gauss PDF – 3 (*Frisch*, 1995).

Fig. 3 presents dependencies of the flatness on the time scale 1/τ for two cases when long enough time intervals were available - December 19, 2015 (panel *a*) and March 15, 2013 (panel *b*). For both of the cases at scales ~100 sec flatness is close to 3, that is, PDF is close to Gaussian. At panel *a* flatness increases significantly with decreasing of the scale (or increasing of 1/τ) upstream as well as downstream the IP shock. Thus, in this case PDF is not Gaussian and have heavier wings. In this case high level of the ion flow intermittency occur on both sides of the shock front. At panel *b* the deviation of flatness from 3 is negligible for each scale upstream and downstream the IP shock. That is, low intermittent flow occur in this case before and after registration of the shock front. Thus, IP shocks do not change intermittency level in the magnetosheath.

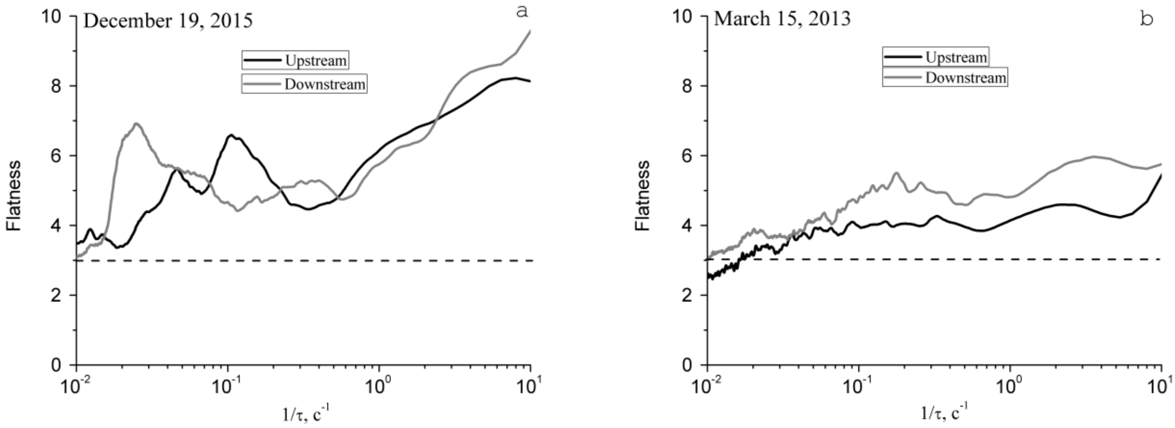

Figure 3. Flatness versus time scale upstream (black line) and downstream (grey line) the interplanetary shock on (**a**) - December 19, 2015; and (**b**) - March 15, 2013. Dashed lines mark flatness value 3 inherent for gaussian probability distribution function.

3. Summary and discussion

Magnetosheath plasma turbulence plays a crucial role in the energy transport and processes of plasma heating in the near-Earth space. However, kinetic scale part of the turbulent cascade in the magnetosheath is not studied completely yet. In the present study large scale structures (such as interplanetary shocks) influence on the plasma turbulence in the magnetosheath is considered. Four cases of IP shocks registration are analyzed in the paper. The results can be summarized as follows:

- Power spectral density of the kinetic-scale ion flux fluctuations increases by one order of amplitude downstream the IP shock front for tree of four cases. This result is consistent with the results of (*Pitňa et al*., 2016) obtained in the solar wind. In one case PSD increases by the factor of 250. This case refers to the most slow IP shock with the highest θ_{BN}^{IP} angle.
- In half of the cases spectra slope of the kinetic part of the spectra do not change with IP shock propagation. However, in other cases steepening as well as flattening of the spectrum occur. Due to the absence of statistics no conclusions can be done concerning proportionality between spectral slopes upstream and downstream IP shocks.
- Exponential cutoff of the kinetic part of the spectra does not observed in the magnetosheath downstream the IP shock while this is the case for half of the events in the solar wind (*Pitňa et al*., 2016). We suggest that exponential cutoff of the spectra is due to the high solar wind velocities downstream the IP shock, which do not occur in the magnetosheath.
- According to case study, IP shocks do not change a level of the ion flow intermittency. This fact was shown both for cases with high and low intermittency level in the upstream plasma flow in the magnetosheath.

Presented results point out that IP shocks seem not to change the features of the turbulent cascade and properties of the probability distribution function in the magnetosheath plasma.

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