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EVOLUTION OF RAPID FLUCTUATIONS OF THE PLASMA PARAMETERS DURING THE CROSSING OF THE EARTH'S MAGNETOSHEATH

L. Rakhmanova, M. Riazantseva, G. Zastenker

Space Research Institute of Russian Academy of Sciences, 84/32 Profsoyuznaya Street, Moscow, Russian Federation, 117997

Abstract. We present a case study of a flank magnetosheath crossing by the Spectr-R satellite. Rapid measurements of the ion flux value and its direction with 31 ms time resolution provided by the BMSW instrument are examined at different distances from the magnetosheath boundaries – the bow shock and the magnetopause. The magnetosheath behind the quasi-perpendicular bow shock is analyzed. Time resolution of data is sufficient for observation of frequency spectra of plasma fluctuations either in MHD and ion kinetic scales. We examine evolution of spectral parameters such as power density, slopes and break frequency together with evolution of properties of a probability distribution function. We find out that (i) power spectral density rises toward the MSH boundaries, (ii) spectra slopes do not change significantly across the magnetosheath, (iii) break frequency of the fluctuations grows toward the magnetopause. We demonstrate that plasma can be less intermittent in the middle MSH comparing to its boundaries.

1. Introduction

Near-Earth space plasma is known to be turbulent for decades (e.g. *Tu and Marsch*, 1995). Nowadays the solar wind (SW) turbulence is well discussed from MHD to electron kinetic scales (see review by *Alexandrova et al*. (2013) and references therein). The Earth's magnetosheath (MSH) turbulence is less studied despite its crucial role in the solar wind– magnetosphere interaction. Basing on in-situ measurements the turbulent cascade in the MSH was studied at MHD scales both for plasma and magnetic field (e.g. *Shevyrev et al*. 2003; *Shevyrev and Zastenker*, 2005). At MHD scales ($f<f_{ci}$,.f_{ci} is ion gyro-frequency) fluctuations were shown to follow Kolmogorov spectra $\sim f^{-5/3}$ at the MSH flanks (*Alexandrova et al*., 2008) and $\sim f^{-1}$ just behind the bow shock in the subsolar MSH (*Czaykowska et al.*, 2001). At kinetic scales ($f>f_{ci}$) only magnetic field fluctuations are generally considered (e.g. *Rezeau et al.*, 1999; *Mangeney et al.*, 2006; *Alexandrova et al*., 2008; *Huang et al*., 2014). In this frequency range the steepening of the spectra is observed: spectra follow $\sim f^{-s}$ law with *s* ranging from 2 to 3. Plasma fluctuations in the MSH at the kinetic scales were considered only with the help of indirect measurements (e.g. *Lacombe et al*., 1995) for the lack of plasma data with a sufficient time resolution.

Studies of turbulence in the SW as well as in the MSH based on direct plasma measurements were presented only recently. Such investigation became possible after Spectr-R satellite launching in 2011. The BMSW instrument on board the Spektr-R satellite provides measurements of the plasma parameters with a time resolution 31 ms.

Investigations of the density fluctuations measured by the BMSW in the SW were reported by (*Šafránková et al*., 2013a, 2015; *Chen et al*., 2014). Velocity fluctuations spectra and their comparison with the density ones are discussed in (*Šafránková et al*., 2013a, 2016). Statistical study of the MSH turbulent cascades based on ion flux measurements from BMSW was presented by *Riazantseva et al.* (2016). The authors conducted a statistical comparison between the turbulent spectra and features of a probability distribution function in the MSH and SW without respect to the different regions inside the MSH. A dynamic of the turbulence features during plasma transfer through the MSH was not addressed in that paper.

In the present paper we study an evolution of small-scale plasma fluctuations and their properties of turbulence with the change of distance to the MSH boundaries with the help of the BMSW measurements. We analyze the power density of plasma fluctuations, shape of fluctuations spectra and change of structure functions properties while the satellite moves from the magnetopause to the bow shock.

2. Observations

The BMSW (Fast Solar Wind Monitor) instrument (*Zastenker et al*., 2013, *Šafránková et al.,* 2013b) provides measurements of the plasma parameters - ion flux value and its direction, proton density, bulk and thermal velocity – with a time resolution 31 ms. The ion flux direction is characterized by the polar angle θ - a deviation of a flux vector from the Sun-Earth line. The ion flux value fluctuations are supposed to represent mostly fluctuations of ion density variations (see e.g. *Pitna et al*., (2016) for a comparison between ion flux and density spectra). We conjecture that polar angle fluctuations represent fluctuations of plasma bulk velocity. BMSW measurements in the MSH are reliable for $\theta<25°$ due to the increasing errors of ion flux value determination for larger angles (see *Gagua et al*., 2009).

The flank MSH crossing under study takes place on February 9, 2012. Spektr-R crosses the magnetopause at 09:43 at $\{6; 2; 10\}_{GSE}$ R_E and enters the SW at 12:24 at $\{4; 4; 13\}_{GSE}$ R_E. The ion flux and polar angle measurements are shown by black lines in Fig. 1a and 1b respectively. Grey line in Fig. 1a shows the SW ion flux measurements by Geotail located upstream from the bow shock at $\{30; -6; 4\}_{GSE}$ R_E. The SW data is shifted by a plasma propagation time (~480 sec). One can see that increase of MSH ion flux toward the bow shock is likely to be due to the SW ion flux increase. Plasma flow is undisturbed except for the abrupt ion flux enhancement at 10:03-10:06 accompanied by a significant rotation of the flux vector. The flux enhancement (though significantly longer) is seen both in the SW and MSH hence it cannot be due to the magnetopause motion. We exclude time interval 10:03-10:06 UT from the study because of the polar angle value $\theta > 25°$. The angle between the interplanetary magnetic field and the bow shock normal - θ_{Bn} – exceeds 45° during the whole interval; thus we deal with the MSH behind the quasi-perpendicular bow shock.

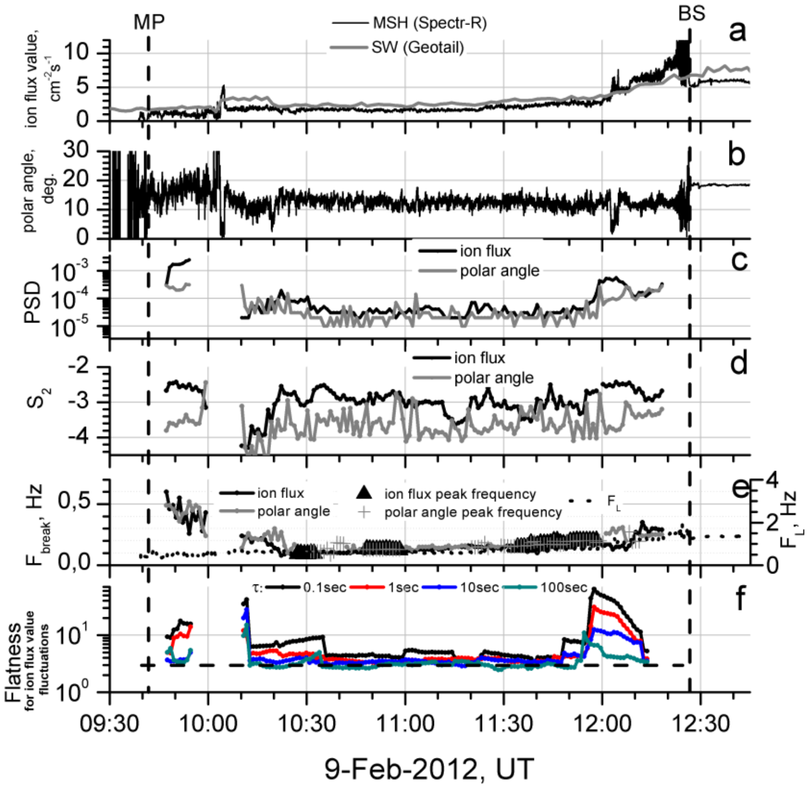

Figure 1. Evolution of parameters through the MSH: **a** - ion flux value in SW (grey line) and in MSH (black line); **b** – MSH polar angle; **c-e** – PSD, spectra index S_2 and break frequency of the ion flux value (black line) and polar angle (grey line) fluctuations, dotted line in panel e shows the inertial length frequency; **f** — flatness of ion flux value fluctuations at scales 0.1, 1, 10 and 100 sec.

For the further analysis we divide the interval into 142 intervals with duration of 512 sec (16 000 data points) moved away by 1 min from one another (i.e. intervals are overlapped by 252 sec). We calculate Fourier spectra at each interval. One part of the spectra can be approximated with two power laws with slopes S_1 and S_2 separated with the break frequency F_{br}: S_1 is close to -5/3 as predicted by Kolmogorov's theory, S_2 ranges from -4 to -2; $F_{break}=0.9\pm0.5$ Hz (*Riazantseva et al.*, 2016). Generally, frequency spectra in the MSH as well as in the SW may be approximated in such manner. However inside the MSH another type of spectra may be observed. These spectra exhibit a broad peak at frequencies close to the break (like shown by *Alexandrova et al.*, 2008). Thus, one can observe spectra at MHD scales (below the break) and at kinetic scales (above the break). We distinguish 3 regions inside the MSH: the middle MSH (11:00-11:20 UT), the magnetopause vicinity (09:43-10:03 UT) and the bow shock vicinity (12:04-12:24 UT). Fig. 1c-e shows time evolutions of parameters of the fluctuations spectra: the power spectral density (PSD) of the ion flux value (black line here and below) and polar angle (grey line here and below) fluctuations at 2±0.1 Hz, S_2 and F_{break}. Crosses in Fig 1e denote spectra with peak and refer to a peak frequency. All the data points in Fig. 1c-e refer to a center of 512 sec intervals used for calculations. Mean values of the analyzed parameters at each location in the MSH are summarized in Table 1. PSD of the high frequency fluctuations grows toward the magnetopause and the bow shock. However, the growth rate of the PSD of ion flux value fluctuations toward the magnetopause is higher than the growth rate of PSD of the polar angle fluctuations. The slope of the ion flux value fluctuations spectra seems to be slightly smaller in the middle MSH - -3.0±0.2 -

comparing to regions near the boundaries - -2.6±0.1. The slope of the high frequency part of polar angle fluctuations spectra at kinetic scales stays nearly constant across the MSH being -3.7±0.3 in the middle MSH and -3.4±0.2 near the boundaries. In the magnetopause vicinity the obtained value is well consistent with the one reported by *Rezeau et al.* (1999) for magnetic field fluctuation spectra -3.4. Just behind the bow shock the obtained slope is somewhat less than the reported previously by *Czaykowska et al*. [2001] for magnetic field fluctuation spectra - -2.6.

The break frequency of fluctuations spectra decreases from 0.4±0.1 Hz in the magnetopause vicinity to 0.13±0.01 Hz in the middle MSH and then grows slightly to 0.25±0.05 Hz at the bow shock for both quantities. Generally a spectra break is supposed to be associated with ion cyclotron frequency (*Alexandrova et al*., 2008; *Czaykowska et al*., 2001) or inertial length frequency (*Šafránková et al*., 2013, 2015). Dotted line in Fig. 1e shows the inertial length frequency F_L, defined as $F_L = V/2\pi L$, where $L=v_A/\omega_C$ (v_A is an Alfven speed and ω_C is the proton gyro-frequency and V is a bulk velocity). A close relation between break frequency of plasma fluctuations and inertial length frequency in the middle MSH and just behind the bow shock is observed. On the other hand inertial length frequency does not change toward the magnetopause. Upstream IMF (*Geotail* data, not shown here) and ambient ion flux stay nearly constant. Hence, the break frequency change cannot be explained by the change of any characteristic plasma frequency. We conjecture the specific character of turbulence near the magnetopause leading to the growth of the break frequency.

Space plasma turbulence is known to be intermittent, i.e. the probability distribution function (PDF) does not follow the Gaussian distribution (e.g. *Bruno et al*., 2003; *Budaev*, 2015). The degree of non-Gaussianity can be characterized by an increase of the flatness coefficient K toward the small scales, where K is defined as the 4-th order moment of PDF $K(\tau)=S_4(\tau)/S_2^2(\tau)$, where $S_p(\tau)=<(n(t+\tau)-n(t))^p>$ (Bruno et al., 2003). K=3 for Gaussian distribution and K>3 for distributions with heavier tails. Fig. 1f shows time evolution of the flatness calculated for the ion flux data at time scales τ=0.1, 1, 10, 100 sec. The flatness is calculated on 15 min intervals. According to Fig. 1f the level of MSH plasma intermittency grows toward the boundaries. In the middle MSH non-intermittent turbulence may be observed. *Yordanova et al.* (2008) reported more intermittent turbulence at larger distances from the quasi-parallel bow shock. This discrepancy may be caused by considering MSH behind the bow shock of different types.

Table 1

Parameter		At the MP	Middle MSH	At the BS
PSD at 2 Hz	ion flux value	10^{-3}	10^{-5}	10^{-4}
	polar angle	10^{-4}	10^{-5}	10^{-4}
S_2	ion flux value	-2.6±0.1	-3.0±0.2	-2.6±0.1
	polar angle	-3.4±0.2	-3.7±0.3	-3.4±0.2
F_{break}, Hz	ion flux value	0.4±0.1	0.13±0.01	0.25±0.05
	polar angle			

3. Summary and discussion

Magnetosheath plasma carries energy from the solar wind to the Earth's magnetosphere. Processes taking place in the MSH should be studied not only at large scales (~ Earth's radii) but also at small scales (~ion gyroradii). The MSH plasma is turbulent and its turbulence differs from the SW one for the presence of boundaries. In order to study MSH turbulence not only magnetic field but also plasma data is worth to be examined. We demonstrate an evolution of plasma fluctuations and plasma turbulence properties across the Earth's magnetosheath at kinetic scales. Our results can be summarized as follows.

- Power spectral density of the high frequency fluctuations grows toward the MSH boundaries. At the magnetopause PSD of ion flux value fluctuations is higher than the one of the polar angle fluctuations.
- High frequency part of spectra of the ion flux fluctuations are usually slightly steeper in the middle MSH than at its boundaries. Spectra of the polar angle fluctuations are steeper than the ones of the ion flux fluctuations; the slope of the spectra does not change across the MSH.
- For both quantities the break frequency of fluctuations spectra decreases from 0.4±0.1 Hz at the magnetopause to 0.13±0.01 Hz in the middle MSH and then grows slightly to 0.25±0.05 Hz at the bow shock. The increase of the break frequency toward the bow shock can be attributed to the increase of background plasma parameters, i.e. inertial length frequency. However, the break frequency increase toward the magnetopause is not accompanied by changes of ambient plasma or magnetic field. Thus, the specific character of turbulence seems to take place near the magnetopause.
- Plasma turbulence is shown to be more intermittent near the boundaries comparing to the middle MSH.

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