

Features of the Spectral Characteristics of Plasma Fluctuations in Different Large-Scale Streams of the Solar Wind

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Abstract—The turbulent characteristics of plasma fluctuations in the solar wind (SW) may substantially change depending on the SW conditions. Large-scale streams of different types, such as undisturbed slow solar wind, fast solar wind, interplanetary coronal mass ejection (EJECTA), magnetic cloud (MC), the compression region at the boundary between fast and slow streams (CIR), and the compression region in front of the EJECTA/MC (SHEATH), are usually characterized by specific plasma parameter values, which may influence turbulent cascade formation. In this paper, we analyze the properties of the spectra of ion flux fluctuations in the SW in the region of transition from the magnetohydrodynamic (MHD) scale to the kinetic one. The analysis is based on measurements carried out with the BMSW plasma spectrometer onboard the SPEKTR-R spacecraft with a high time resolution. The observational intervals inside the SW streams of different large-scale types are considered, and the main turbulence characteristics in these streams are compared. It was shown that the properties of the fluctuation spectra may strongly depend on the SW type; in particular, the spectrum of kinetic-scale fluctuations usually becomes much steeper inside the MC regions and the compression regions in front of them, as well as in the CIR. The characteristics of the fluctuation spectra on MHD scale are less dependent on the type of large-scale SW structures, and, on average, they correspond to the Kolmogorov spectra. However, it can be noted that the smallest spectral slopes are observed in the slow undisturbed solar wind, which is indicative of the differences from the traditional Kolmogorov model of the developed turbulence.

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1. INTRODUCTION

There has recently been increasing interest in the study of the cascade of turbulent fluctuations in the solar wind (SW) plasma, particularly, on the scales of order of the ion and electron gyroradii. This is connected with active development of SW models that consider the kinetic effects rather than just the classical magnetohydrodynamic (MHD) approach (Howes et al., 2008; Schekochihin et al., 2009; Servidio et al., 2014). In particular, analysis of the turbulence spectrum in a wide range of scales makes it possible to explain the energy transfer mechanisms in the turbulent cascade between the onset and dissipation regions, followed by heating and accelerating of the SW particles. Until recently, these studies were limited due to the lack of systematic measurements of the plasma parameters in the SW with a time resolution sufficient to study the kinetic interval of the turbulent cascade. The papers published on this subject (Unti et al., 1973; Celnikier et al., 1987; Kellogg and Horbury, 2005; Chen et al., 2012) were sporadic up until 2011, when the plasma parameters were measured with the BMSW instrument (the abbreviation BMSW orig-

inates from the Russian abbreviation of the fast monitoring of the solar wind) onboard the SPEKTR-R spacecraft with a record time resolution of about 31 ms (Zastenker et al., 2013; Šafránková et al., 2013). At the same time, the studies of fluctuations of the interplanetary magnetic field (IMF) with a rather high time resolution have been regularly carried out for the last two decades (e.g., a review by Alexandrova et al. (2013)); however, they fail to provide a complete pattern without the corresponding measurements of fluctuations of the plasma parameters. The spectrum of turbulent fluctuations of the IMF in the region of transition from the MHD scale to the kinetic one can generally be described by two linear dependences (on each of the scales) with a sharp knee when passing from scale to scale (Alexandrova et al., 2013; Bruno et al., 2013). On average, the MHD-scale spectrum corresponds to the $-5/3$ slope of the classical Kolmogorov model (Kolmogorov, 1941; Frish, 1995). On the ion-kinetic scales, the spectrum becomes steeper, and its average slope reaches -2.8 (Alexandrova et al., 2013; Bruno et al., 2013). In papers by Howes et al. (2008) and Schekochihin et al. (2009), the spectrum steepening

due to the increase in the kinetic Alfvén turbulence contribution was analyzed. However, this model predicts a smaller absolute value of the spectrum slope as compared to that observed in the experiments, approximately $-7/3$. Howes et al. (2008) showed that the higher slopes observed in the experiments appear with allowance for Landau damping. The greater steepness of the spectra is also predicted by the models considering the plasma intermittency (Boldyrev and Perez, 2012) and the fractality of its structure (Zelenyi and Milovanov, 2004). For the fluctuation spectra of the directed and thermal SW velocity, a shape with two characteristic slopes and a distinct knee point is also typical (Šafránková et al., 2016), while the spectra of the density fluctuations more often exhibit the flattening in the knee vicinity (Unti et al., 1973; Celnikier et al., 1987; Šafránková et al., 2015). Chandran et al. (2009) showed that this flattening can form as a result of the superposition of the spectra of the density fluctuations of the Alfvén turbulence and the kinetic Alfvén turbulence. In addition, specific features in the fluctuation spectra can be formed near the transition zone between the MHD and kinetic scales due to the different contributions of the kinetic Alfvén waves, different plasma instabilities, and individual coherent structures (Lion et al., 2016). These features are often observed in the spectra of the ion flux fluctuations (Riazantseva et al., 2017a; 2017); however, the mechanisms responsible for the formation of a given shape of the fluctuation spectrum have not yet been fully described (Howes et al., 2008). The characteristic frequency of the transition to the kinetic scale depends on the plasma parameter beta β_p (the ratio of the thermal plasma pressure to the magnetic pressure) (Chen et al., 2014a; Šafránková et al., 2016). As a rule, the value of β_p reflects the SW stream type. For example, $\beta_p \ll 1$ is characteristic of the MC and EJECTA, while $\beta_p \geq 1$ is typical of the compression regions and the heliospheric current layer (e.g., Yermolaev et al., 2009). Moreover, it was noted in some papers (Bruno et al., 2014; Riazantseva et al., 2017) that the fluctuation spectrum shape may also depend on the global properties of the SW stream rather than only on the local values of the plasma parameters. However, no systematic comparison of the turbulence characteristics in different large-scale SW structures has been made until now. In this paper, we analyze the characteristics of the spectra of turbulent fluctuations in the ion flux of the SW on MHD and kinetic scales in large-scale SW streams of different types. In particular, we pay special attention to the problem of the anomalous steepening of fluctuation spectra on kinetic scales; there was a clear connection between the probability of the appearance of anomalous steepening with the large-scale parameters of the surrounding plasma (Riazantseva et al., 2017).

2. DATA AND ANALYSIS TECHNIQUE

In the study, we use data with a high time resolution obtained by the BMSW plasma spectrometer (Zastenker et al., 2013; Šafránková et al., 2013) of the PLASMA-F experiment onboard the SPEKTR-R spacecraft (SC) (Zelenyi et al., 2013). Regular measurements of the ion flux vector in the SW and the magnetosheath (MSH) with a time resolution of 31 ms and the measurements of the density, velocity, and temperature of protons and the relative content of helium ions with a resolution of 3 s (a sweeping mode) have been carried out since 2011. In some cases (in adaptive mode), the density, velocity, and temperature of protons can be measured with the best time resolution, 31 ms. We analyze the longest time series of data on the SW ion flux obtained with the best time resolution. Measurements of the SW parameters are used only to calculate the mean values on the considered intervals. The high time resolution of the measurements allows us to analyze the properties of the turbulent plasma fluctuations on scales of the ion gyroradius and higher. The instrument and its operating principles are described in detail by Zastenker et al. (2013) and Šafránková et al. (2013). It should be stressed that, since the IMF was not measured onboard the SPEKTR-R SC, we used the data of the Magnetic Field Investigation (MFI) instrument onboard the WIND SC (Lepping et al., 1995), which are available on the CDAWeb resource (<https://cdaweb.sci.gsfc.nasa.gov>). The time delay between measurements of SPEKTR-R SC and WIND SC (which is rather distant approximately 150–250 Re), was made according to the SW propagation time and defined more accurately by matching the boundaries of large-scale plasma structures.

The high-apogee orbit of the SPEKTR-R SC (Zelenyi et al., 2013) and the constant orientation of the BMSW instrument toward the Sun (within $\pm(5^\circ-10^\circ)$) makes it possible to carry out long-term continuous observations of the SW. However, due to the limited capabilities of the actual telemetric channel, only $\sim 10\%$ of the high-resolution data of the instrument have been transmitted to the data center on the Earth to date. For this study, we selected long-term (not less than 3 h) series of measurements of the SW ion flux in 2011–2015, which amounts to ~ 500 h of measurements. To analyze the properties of the spectra of the ion flux fluctuations, each of the intervals was divided into shorter subintervals, the length of which was ~ 17 min. The interval length was determined by the number of points that is optimal for fast Fourier transform and by the smallest analyzed frequencies of the fluctuation spectrum, $\sim 10^{-2}$ Hz. Each of the next analyzed interval was shifted in time by the distance, which is half of the duration of the initial interval (i.e., by ~ 8.5 min). Fast Fourier transform with the subsequent filtration was used to calculate the frequency spectrum of the ion flux fluctuations on the current interval. The considered data

allow the fluctuation spectra on the frequencies to 16 Hz to be calculated; however, as shown earlier by Chen et al. (2014b), the noise level increases at frequencies higher than ~ 10 Hz, while the signal-to-noise ratio drops, which should be taken into account if the flux values are low. Thus, the presently considered spectra of fluctuations are calculated in a frequency range of 10^{-2} to 10 Hz.

The fluctuation spectrum has a classical shape exhibiting two slopes (on the MHD and kinetic scales, respectively) and a sharp knee in the SW only in 50% of cases (Riazantseva et al., 2017a; 2017). In other cases, different features (such as a plateau, a peak, no knee, and an anomalous steepening) in the scale-to-scale transition zone can be observed. Nevertheless, regardless of the shape of fluctuation spectra, the spectral ranges corresponding to the MHD and kinetic scales can be isolated via exclusion of the scale-to-scale transition zone, where the fluctuation spectrum may contain a plateau or a peak. Thus, as a rule, the slopes of the spectra can unambiguously be determined on these scales, while the frequency of the knee in the spectrum can be determined only for the spectra of a classical shape. Consequently, in this study, we analyze only the slopes of the spectra (on the both MHD and kinetic scales) for the observational data volume as a whole, not for data divided into spectrum types according to their shape.

Figure 1 presents examples of the fluctuation spectra of the ion flux for two intervals: in the slow SW from 1608 to 1625 UT on June 20, 2014 (a solid gray curve) and in the SHEATH region in front of the MC from 1226 to 1243 UT on September 30, 2012 (a dotted black curve). The spectra are normalized by power for better comparison. In addition to the mean slopes of the spectrum on the MHD and kinetic scales (P_1 and P_2 , respectively), the slopes were also determined in two frequency ranges of 3–5 and 6–8 Hz (the corresponding frequency ranges are shown by light- and dark-gray rectangles in the plot) to estimate the steepening degree of the spectra on the kinetic scale. On the MHD scale, the slopes of the fluctuation spectra are approximately the same ($P_1 = -1.62 \pm 0.04$ and -1.67 ± 0.07 for the first and second intervals, respectively) and close to the $-5/3$ slope of the classical Kolmogorov spectrum. On the kinetic scale, as can be expected, the spectra become steeper (see the Introduction), and their slopes are $P_2 = -3.2 \pm 0.2$ and -3.6 ± 0.2 on average for the first and second intervals, respectively. It should be stressed that, in the first case, the spectrum demonstrates the same slope in the whole frequency range of the kinetic interval ($P_2(3-5 \text{ Hz}) = -3.3 \pm 0.2$, $P_2(6-8 \text{ Hz}) = -3.3 \pm 0.2$), i.e., the spectrum decreasing can be approximated linearly. At the same time, for the second case, the spectrum becomes nonlinearly steeper with increasing frequency ($P_2(3-5 \text{ Hz}) = -3.3 \pm 0.2$, $P_2(6-8 \text{ Hz}) = -4.2 \pm 0.2$). Comparison of the slopes in the specified frequency ranges shows the steepening

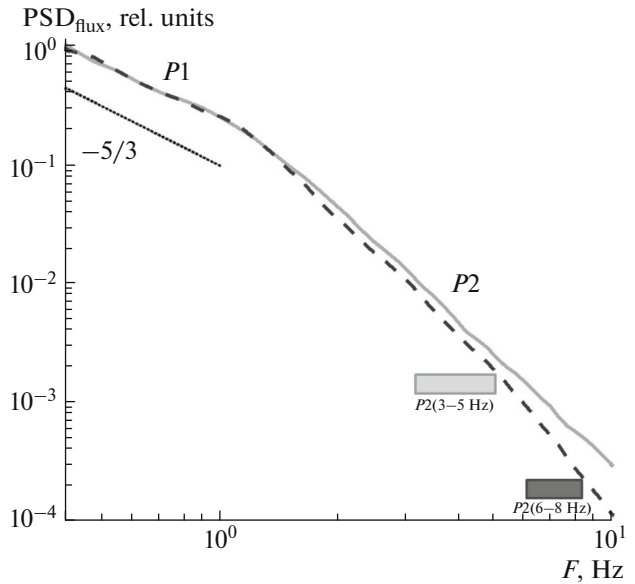


Fig. 1. Examples of the normalized spectra of fluctuations in the SW ion flux (PSD is the probability distribution function) for intervals from 1608 to 1625 UT on June 20, 2014 (a solid gray curve), and from 1226 to 1243 UT on September 30, 2012 (a dotted black curve). Rectangles indicate a high-frequency range of 3–5 Hz (colored light-gray) and a range of 6–8 Hz (colored dark-gray), within which the slopes of the spectrum are calculated. A dashed black curve shows the slope of the classical Kolmogorov spectrum of fluctuations.

degree of the fluctuation spectrum on kinetic scales. The dependence is close to linear if the slopes are the same in all ranges. Applying the described technique to all of the SW types, we considered ~ 3262 spectra, which is four times greater than the amount of statistics in the papers by Riazantseva et al. (2017a, 2017).

With the use of the catalog developed by Yermolaev et al. (2009) (<ftp://ftp.iki.rssi.ru/pub/omni/catalog/>), all considered intervals were linked to the large-scale types of the SW, such as interplanetary coronal mass ejection (EJECTA), magnetic clouds (MCs), the compression regions that form due to the interaction of a high-speed SW stream from a coronal hole and a slow stream from a streamer belt (CIR), the compression regions in front of the EJECTA/MC (SHEATH), high-speed SW (as a rule, the streams from coronal holes), and regions of the undisturbed slow SW (as a rule, the streams from coronal streamers). In front of the compression regions CIR and SHEATH, interplanetary (IP) shock waves may be observed; they may contribute to variations in the SW parameters and characteristics of the turbulent cascade of plasma fluctuations (e.g., Pitňa et al., 2016; Riazantseva et al., 2017b). However, this effect is observed in the immediate vicinity of the IP shock wave fronts. If the number of IP shock waves is relatively small, their presence cannot significantly influence the statistics analyzed here (Yermolaev et al., 2009). Consequently, at the

Table 1. Mean values of the plasma and IMF parameters and the slopes of the spectra on the MHD and kinetic scales for different large-scale SW types

| | All intervals | Slow SW | Fast SW | EJECTA | SHEATH–EJECTA | MC | SHEATH–MC | CIR |
|--|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Number of intervals | 3262 | 1241 | 301 | 717 | 185 | 292 | 197 | 329 |
| Number of intervals, % | 100% | 38.0% | 9.2% | 22.0% | 5.7% | 9.0% | 6.0% | 10.1% |
| $\langle N \rangle$, cm^{-3} | 11.2 ± 0.1 | 10.4 ± 0.2 | 8.1 ± 0.3 | 9.6 ± 0.2 | 10.4 ± 0.3 | 8.0 ± 0.3 | 16.0 ± 0.6 | 20.6 ± 0.7 |
| $\langle V \rangle$, km/s | 406 ± 1 | 368 ± 1 | 471 ± 1 | 420 ± 2 | 412 ± 1 | 483 ± 2 | 446 ± 5 | 359 ± 2 |
| $\langle T \rangle$, eV | 6.6 ± 0.1 | 6.1 ± 0.2 | 12.1 ± 0.6 | 2.9 ± 0.1 | 9.1 ± 0.3 | 5.0 ± 0.2 | 12 ± 0.5 | 7.9 ± 0.3 |
| $\langle Na/Np \rangle$, % | 3.8 ± 0.1 | 3.5 ± 0.1 | 2.5 ± 0.1 | 3.8 ± 0.1 | 3.1 ± 0.1 | 8.5 ± 0.2 | 3.2 ± 0.1 | 3.1 ± 0.1 |
| $\langle B \rangle$, nT | 7.6 ± 0.1 | 7.1 ± 0.2 | 7.7 ± 0.2 | 6.5 ± 0.1 | 7 ± 0.2 | 8.5 ± 0.3 | 9.2 ± 0.2 | 10.3 ± 0.2 |
| $\langle \beta_p \rangle$ | 0.72 ± 0.02 | 0.76 ± 0.02 | 0.93 ± 0.08 | 0.54 ± 0.06 | 0.96 ± 0.07 | 0.57 ± 0.05 | 0.97 ± 0.06 | 0.61 ± 0.03 |
| $\langle P_1 \rangle$ | -1.6 ± 0.01 | -1.53 ± 0.01 | -1.60 ± 0.02 | -1.71 ± 0.02 | -1.55 ± 0.03 | -1.56 ± 0.02 | -1.66 ± 0.02 | -1.63 ± 0.02 |
| $\langle P_2 \rangle$ | -2.8 ± 0.01 | -2.53 ± 0.02 | -2.76 ± 0.04 | -2.80 ± 0.03 | -2.99 ± 0.03 | -3.18 ± 0.02 | -3.20 ± 0.04 | -3.18 ± 0.03 |
| $\langle P_2 \rangle$, 3–5 Hz | -2.76 ± 0.01 | -2.59 ± 0.02 | -2.78 ± 0.03 | -2.76 ± 0.02 | -2.95 ± 0.03 | -2.92 ± 0.03 | -3.00 ± 0.03 | -3.02 ± 0.02 |
| $\langle P_2 \rangle$, 6–8 Hz | -2.88 ± 0.02 | -2.48 ± 0.03 | -2.75 ± 0.05 | -2.87 ± 0.04 | -3.04 ± 0.05 | -3.57 ± 0.04 | -3.56 ± 0.06 | -3.37 ± 0.04 |

present stage, we analyze all cases regardless of the presence or absence of IP shock waves in front of the compression regions.

Table 1 presents the percentage ratios between the intervals observed in different large-scale SW streams and the mean values of the plasma and IMF parameters for the selected intervals. It should be stressed that these values may somewhat differ from the typical parameters, on average, of these or those large-scale SW structures (Yermolaev et al., 2009). This is connected with the sampling limitation and, in particular, with specific features of the instrument that do not enable one to measure the speed in SW higher than ~ 700 km/s (Pitňa et al., 2016).

3. ANALYSIS OF THE SPECTRAL CHARACTERISTICS OF ION FLUX FLUCTUATIONS ON THE MHD AND KINETIC SCALES IN SW OF DIFFERENT TYPES

The extended statistics of the spectra of the ion flux fluctuations in the SW considered here made it possible to sort them by large-scale SW types and to determine the difference between the characteristics of the spectra of the ion flux fluctuations. Figure 2 presents the mean slopes of the spectra on the kinetic scale with respect to the analogous parameters on the MHD scales for different SW structures. For all of the considered intervals, the slopes are on average $\langle P_1 \rangle = -1.6$ and $\langle P_2 \rangle = -2.8$, respectively (see Table 1), which is consistent with observations of fluctuations of both the plasma and magnetic parameters in the SW and with current turbulence models (see the Introduc-

tion). However, it can be noted that the mean slopes for different large-scale SW structures may substantially differ (Fig. 1 and Table 1). For example, shallower slopes are characteristic of slow SW on both the MHD and kinetic scales. At the same time, the slope on the MHD scales is $\langle P_1 \rangle = -1.53$, which noticeably differs from the $-5/3$ spectrum slope in the classical Kolmogorov approach. For the regions of the fast SW, MC, and SHEATH in front of the EJECTA, the observed slopes on the MHD scales are smaller in absolute value than the Kolmogorov spectrum slopes. The EJECTA, the SHEATH in front of the MC, and the CIR are characterized by slopes close to the Kolmogorov ones.

On the kinetic scales, the slopes closest to the mean values in the SW are observed in the spectra in fast SW and inside the EJECTA. In the slow SW, the observed slopes are smaller in absolute value than the mean values in the SW. The steepest kinetic-scale slopes (i.e., with the largest absolute values of the slopes) are characteristic of the intervals inside the MC, SHEATH (especially in front of the MC), and CIR regions. It should be stressed that this property may be connected, in particular, with the anomalous steepening of the fluctuation spectra on kinetic scales, which is sometimes observed in the SW (Riazantseva et al., 2017). Below, we will present the results of the analysis of the steepening degree of the fluctuation spectra on kinetic scales for different SW types. Figure 3 shows the set of distributions of the slopes of the fluctuation spectra in two frequency ranges (3–5 and 6–8 Hz) for each of the considered large-scale SW types. Table 1 lists the mean values of the slopes in the specified

ranges. Figure 3a presents the distributions for all of the analyzed intervals. The maxima in the distributions and the mean values of the slopes in the both frequency ranges are close; however, the distribution in a range of 6–8 Hz is significantly wider than the analogous distribution in a range of 3–5 Hz, which reflects the large number of events with the spectrum steepening observed at higher frequencies. The analogous situation is observed for the intervals inside the EJECTA (Fig. 3c) and the SHEATH in front of the EJECTA (Fig. 3e). The situation is substantially different for the fluctuation spectra in undisturbed slow SW (Fig. 3b) and fast SW (Fig. 3d): the distributions of slopes in different frequency ranges are almost the same, and the mean slopes (Table 1) hardly change. Thus, we may assert that steepening of the fluctuation spectra at high frequencies is not typical for these SW types. On the contrary, for the fluctuation spectra observed inside the MC (Fig. 3f) and the SHEATH in front of the MC (Fig. 3h), it is clearly seen that the distribution of the spectrum slopes in a frequency range of 6–8 Hz is considerably shifted toward larger absolute values of the spectrum slopes relative to the analogous distribution in a range of 3–5 Hz. Thus, we may conclude that the fluctuation spectra in this case often exhibit steepening at high frequencies. For the spectra observed inside the CIR regions (Fig. 3g), some tendency toward steepening at high frequencies can also be noted; however, the distribution of slopes in a range of 6–8 Hz is very wide and exhibits no clearly expressed maximum. It should be stressed that the difference between the slopes in different SW types is observed not only in a range of 6–8 Hz but also in a range of 3–5 Hz (Table 1). For example, the smallest in absolute value slopes of the spectra, around -2.6 , are observed for low-speed SW streams. Slope values of approximately -2.8 , which are frequently encountered in the literature, are, as a rule, characteristic of the high-speed streams and those in the EJECTA regions, while the largest slopes of the spectra, from -2.9 to -3.0 , are typical of the SHEATH (in front of the EJECTA and MC), MC, and CIR regions. In general, these values agree with the mean values of the slopes obtained above for the whole frequency range on the kinetic spectral interval.

4. DISCUSSION

The formation of fluctuation spectrum can be determined not only by the values of plasma parameters but also by the type of large scale SW streams (Riazantseva et al., 2017). In this paper, we analyzed the slopes of spectra of the ion flux fluctuations on both the MHD and kinetic scales within different SW types. It was shown that the spectrum slopes within individual isolated SW types may essentially differ from the mean slopes characteristic of the SW as a whole. The spectrum slopes on the MHD scales may vary in wide ranges; however, on average, they corre-

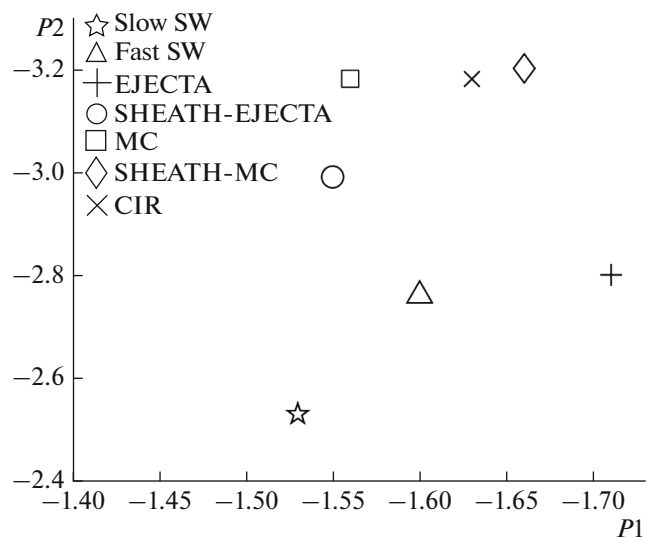


Fig. 2. Mean slopes of the spectra on the kinetic scales P_2 with respect to the mean slopes on the MHD scales P_1 . Different large-scale types of the SW are shown by specified symbols: slow SW (a star), fast SW (a triangle), EJECTA (a right cross), SHEATH in front of EJECTA (a circle), MC (a square), SHEATH in front of MC (a diamond), and CIR (a sidelong cross).

spond to the classical Kolmogorov spectrum of turbulence. For some large-scale SW streams, such as the slow SW, the SHEATH in front of the EJECTA, and the MC, the characteristic spectrum slopes are substantially lower in absolute value than the Kolmogorov spectrum slopes, which suggests that there is no developed turbulent cascade in these streams. Šafránková et al. (2016) showed earlier that minimal absolute values of the slopes of the density fluctuation spectrum are usually observed in the SW with the smallest amplitude of fluctuations, which is characteristic of the slow undisturbed SW. The spectrum slopes observed in the regions of the fast SW, EJECTA, the SHEATH in front of the MC, and CIR are close to the Kolmogorov ones.

Table 1 shows that there is an interrelation between the mean slopes of the fluctuation spectrum and the value of the mean parameters of the SW on kinetic scales. The smallest absolute values of the slopes on the kinetic scale are observed in slow SW with the minimal values of all of the SW parameters. Simultaneously, they are mostly close to the predictions of the kinetic Alfvén turbulence model (Schekochihin et al., 2009). For slow SW, the Landau damping contribution (Howes et al., 2008) is apparently insignificant, while its role in the other regions grows and leads to different steepening degrees for the fluctuation spectra depending on the conditions in the SW. The maximum absolute values of the slopes are typical of MCs, the SHEATH in front of the MC, and the CIR. It should be noted that all three regions are characterized by an enhanced value of the IMF modulus, and the CIR and the SHEATH in front of the MC are also

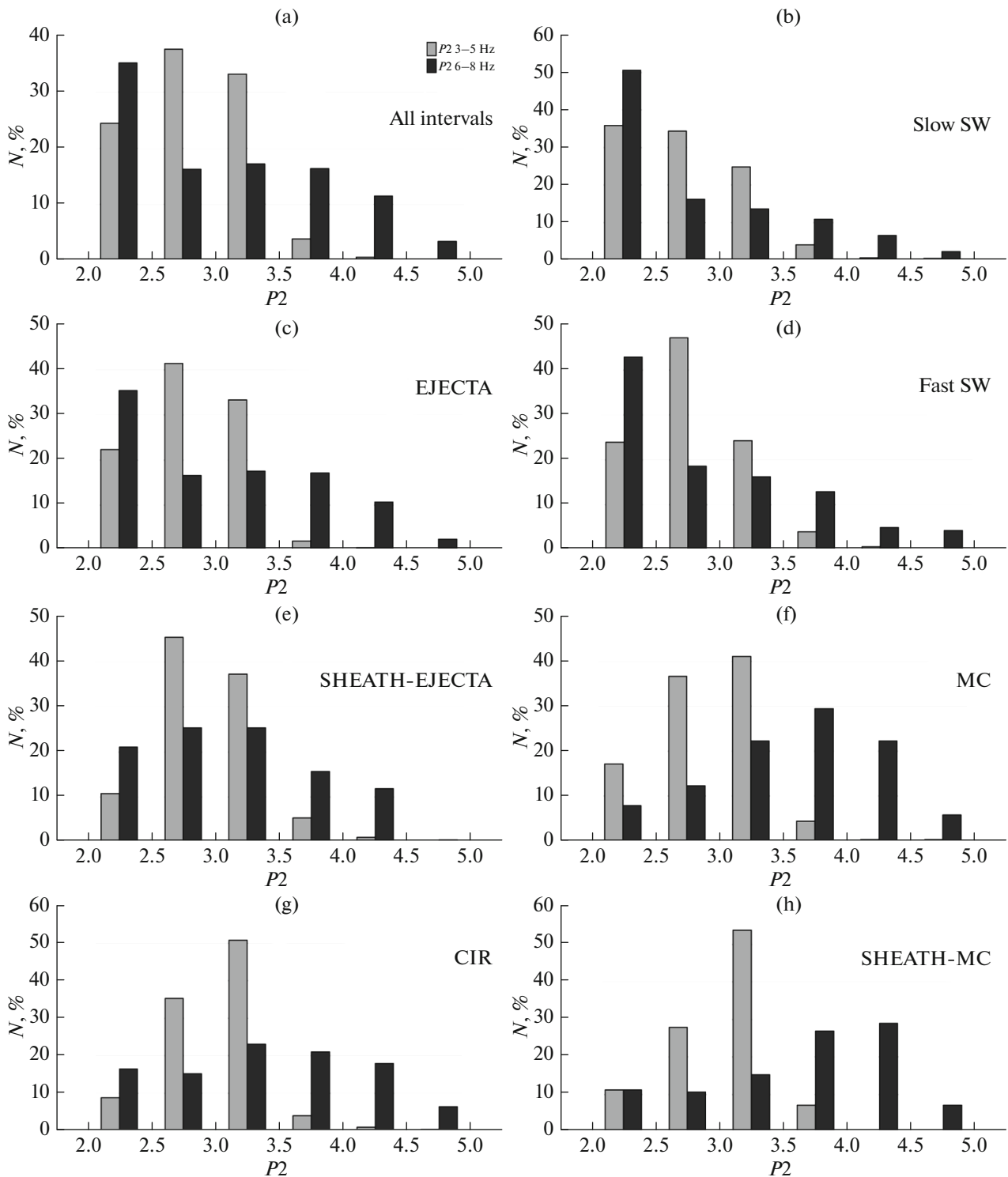


Fig. 3. Distributions of the slopes of the ion flux fluctuation spectra in frequency ranges of 3–5 and 6–8 Hz (colored light- and dark-gray, respectively) for different large-scale SW types: all intervals (a), slow SW (b), EJECTA (c), fast SW (d), SHEATH in front of EJECTA (e), MC (f), CIR (g), and SHEATH in front of MC (h).

characterized by enhanced proton density, while the MC exhibits higher values of the velocity and the relative helium ion content. However, it should be noted that the described tendency is noticeable only on aver-

age and weakly manifests itself in the dependence of the spectrum slopes on the SW parameters in each of the considered intervals. Earlier, Riazantseva et al. (2017) analyzed the dependence of the fluctuation

spectrum shape on the SW parameters. The most clearly distinguished fluctuation spectra were those with nonlinear steepening on kinetic scales, which are characterized by enhanced values of the density, velocity, proton temperature, and relative helium ion content; however, such events were few in relative number (~6%). Conversely, it was also noticed that there is a rather large number of intervals with high values of the velocity and the other SW parameters, which exhibit no steepening of the kinetic-scale spectra. Consequently, in the present paper, we analyzed the slopes of fluctuation spectra on the kinetic scales in two frequency ranges (3–5 and 6–8 Hz) without selecting the SW spectra by shape in the transition zone from MHD scales to kinetic ones. Comparison of the slopes in these frequency ranges makes it possible to distinguish clearly events with spectrum steepening at higher frequencies. Statistical analysis of the slopes allowed us to determine the strongly pronounced steepening of the spectra at high frequencies inside the MC and in the SHEATH regions in front of the MC. A tendency toward spectrum steepening inside the CIR is also observed; however, this group of events should be analyzed further in more detail. In the intervals observed inside the EJECTA and the SHEATH in front of the EJECTA, the tendency toward spectrum steepening is weak. For intervals in the quiet low-speed and high-speed SW, which form closer to the Sun, spectrum steepening at high frequencies is not typical. Howes et al. (2008) pointed out that the linear steepening of the spectrum may be observed in the cases, when the effects connected with the Landau damping are negligible and the spectra conform to the kinetic Alfvén turbulence model, where the exponential steepening of the spectrum is connected with the damping increase. The nonlinear steepening is observed in experiments only in cases in which the Landau-damping contribution is rather high.

The study of spectrum slopes on kinetic scales in fast SW streams is of particular interest. Bruno et al. (2014) showed that, for high-speed SW streams ($V > 450$ km/s), the typical slopes of fluctuation spectra are larger in absolute value than those for low-speed streams. Pitňa et al. (2016) studied spectrum steepening in the downstream regions of interplanetary shock waves, i.e., in regions also exhibiting increased values of the SW speed on average. It was supposed that the spectrum steepening may be connected with acceleration of the dissipation processes at the shock wave fronts. The results above confirm that the spectrum slopes in the high-speed streams are actually on average somewhat larger in absolute value than those in slow SW. The close absolute values of the slopes on the kinetic scales are also characteristic of the EJECTA regions. However, the highest absolute values of the spectrum slopes are observed for the intervals inside the CIR, MC, and SHEATH (in front of the MC and the EJECTA) regions; at the same time, the enhanced mean speeds are typical only of MCs, while the speeds

for the intervals inside the CIR and the SHEATH are on average lower than those in high-speed SW streams. Thus, we may conclude that a key factor in the formation of the fluctuation spectrum on the kinetic scales is the association of the SW speed (or any other SW parameter) with a given large-scale SW type rather than the parameter value itself. In the MC regions and the plasma compression region in front of them, the conditions are created for the formation of spectra with anomalous steepening on kinetic scales, which is connected with acceleration of the dissipation processes in these structures. It can be supposed that such conditions appear not only due to the high value of the speed itself but because there are regions of interaction between SW streams of different speeds, which are most often observed near fast SW streams of different origin: for example, high-speed streams from coronal holes or fast coronal mass ejections.

5. CONCLUSIONS

In this study, we present a statistical analysis of the spectral characteristics of SW ion flux fluctuations based on data from the BMSW instrument onboard the SPEKTR-R SC. This allows the plasma turbulence characteristics to be analyzed on the scales of the ion gyroradius and higher. We considered the dependence of the fluctuation spectra of the ion flux on the both MHD and kinetic scales for different large-scale SW types.

For the MHD scales, it was found that

- the spectrum slopes approximately correspond to the $-5/3$ slope, which is characteristic of the model with the developed isotropic Kolmogorov turbulence, only in the regions of high-speed streams from coronal holes, EJECTA regions, and the plasma compression regions in front of high-speed streams (such as the CIR and the SHEATH in front of the MC);

- the spectrum slopes for slow SW streams, MC regions, and the SHEATH regions in front of the EJECTA are, as a rule, noticeably lower than the Kolmogorov slopes, which is characteristic of the processes of turbulent cascade development in these cases.

For the kinetic scales, it was found that

- the fluctuation spectrum slopes, which are close to those predicted by the kinetic Alfvén turbulence model, are observed only in slow undisturbed SW, the plasma parameters of which are minimal;

- the slopes of fluctuation spectra of the ion flux inside fast streams of SW and EJECTA correspond, on average, to the spectrum slopes of the magnetic field fluctuations observed in the other experiments;

- the largest slopes of the fluctuation spectra are observed in the MC regions and the plasma compression regions SHEATH and CIR;

—the anomalous nonlinear steepening of the fluctuation spectra is usually observed in MCs, the SHEATH in front of the MC, and, to less extent, the CIR.

The more rapid decrease of the fluctuation spectra observed at higher frequencies in comparison to that predicted in the models may be connected with the increase in the Landau damping contribution and the acceleration of the dissipation processes due to the interaction of SW streams of different speeds, which are typical of the specified regions above.

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